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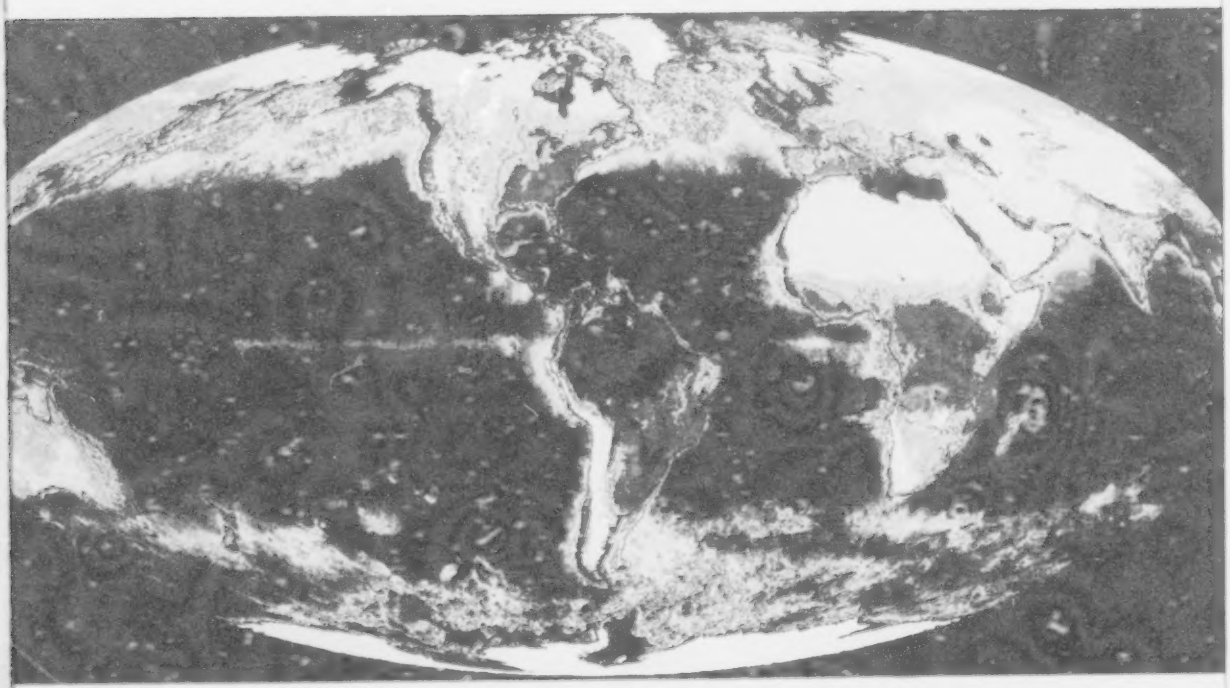
SEMINARS

of the
United Nations Programme on Space Applications



Selected Papers on Remote Sensing Technology

United Nations

Outer Space Affairs Division

A/AC.105/443

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United Nations
1990

Foreword

Since 1972, the United Nations Outer Space Affairs Division, as part of its Programme on Space Applications, has organized and co-sponsored meetings, seminars, training courses and workshops on the application of space technology to assist developing countries in establishing an indigenous technological infrastructure and in developing and implementing local programmes. The United Nations carries out these activities in co-operation with other international and regional organizations and national institutions in accordance with the mandate of the Programme, relevant United Nations General Assembly resolutions, and the recommendations of the Second United Nations Conference on the Exploration and Peaceful Uses of Outer Space (UNISPACE-82) that re-affirmed the importance of establishing and strengthening national and regional mechanisms to promote co-operation in the use of space technology for the benefit of developing countries. Although the Programme on Space Applications conducts a number of activities that are devoted to various fields of space technology, in 1989 it organized activities dedicated particularly to improving information systems in agricultural, geological, oceanographic and coastal resources through remote sensing techniques and to the development of indigenous capability at the local level particularly through educational systems.

This publication comprises selected papers presented at the 1989 activities of the Programme on Space Applications that illustrate the issues relating to the use of space technology in the management of the environment and natural resources, particularly in the developing countries. The scope of the publication extends from a general overview of the use of remote sensing technology for development to specific areas of application, including the assessment of natural vegetation and agricultural systems, the determination and forecast of precipitation, the monitoring of ecological conditions in the coastal environment and the development and implementation of educational curricula and database systems for educators, managers and researchers. In examining the technology available for monitoring the environment and observing physical and biological processes, a number of papers focused on remote sensing instrumentation for aerial photography, current and future radar systems on board Earth resource satellites, multispectral scanner systems on board the Landsat and SPOT satellites and monitoring devices on board meteorological satellites including the United States National Oceanic and Atmospheric Administration (NOAA)

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series, the European Space Agency (ESA) Meteosat series, the USSR Meteor series and the Japanese Maritime Observation Satellite. Because the papers are selected from workshops, training courses and seminars held in various parts of the world, they addressed remote sensing applications corresponding to the particular needs of the regions concerned.

This publication initiates a series of annual United Nations publications dedicated to different fields of space technology applications. These publications aim to promote further international exchange of information and experience as well as disseminate information on United Nations activities in assisting developing countries to utilize space technologies for their social and economic development. They will also be a contribution of the United Nations toward ensuring that the peaceful use of outer space is carried out for the benefit and in the interest of all countries.

V Safronchuk

Vasiliy S. Safronchuk
Under-Secretary-General for
Political and Security Council Affairs

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GAINING ACCESS TO SPACE INFORMATION SYSTEMS: OPPORTUNITIES AND PROBLEMS

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ABSTRACT

This paper provides a brief survey of existing space information systems and their potential for oceanographic and marine applications and activities. The various ground facilities available in the Indian Ocean region and the associated technological, financial, manpower and logistic problems that the developing countries encounter in accessing these space information systems are discussed. The need for effective mechanisms and networks for dissemination and exchange of data and information are identified.

INTRODUCTION

A space information system can be defined as a system that uses space platforms such as satellites or space stations for acquisition, transmission and relay of information and data. As such, all currently orbiting operational satellites can be regarded as space information systems because they are engaged in one way or another, in the acquisition, recording, processing, transmission, relay and exchange of data and information.

TYPES OF SPACE INFORMATION SYSTEMS

Before discussing the matter of access to space information systems, it appears appropriate to survey briefly the various types of satellite systems that currently operate. There can be several ways of classifying and categorizing the multitude of satellites orbiting the Earth today. One way would be to categorize them on the basis of the type of information/data and services they provide. On this basis, space information systems can be broadly categorized into the following five types:

1. Communication satellites;
2. Meteorological satellites;
3. Remote sensing satellites;
4. Scientific satellites other than those for meteorology and remote sensing;
5. Reconnaissance satellites.

This paper, which was presented at the United Nations/Indian Ocean Marine Affairs Co-operation (IOMAC) Workshop on Oceanographic/Marine Space Information Systems, Karachi, Pakistan, 2-6 July 1989, does not necessarily represent the views of the United Nations.

Communication satellites always occupy the geostationary equatorial orbit, about 36,000 km above the Earth's surface, with a 24 hour period which synchronizes with the rotational period of the Earth. Because of this synchronization in time-periods, they act as fixed platforms through which data and information can be conveniently relayed from one part of the Earth to another. Each communication satellite can cover up to 45 per cent of the Earth's surface. Arrangements exist in these satellites to transmit hemispheric beams over the entire coverage zone of the satellite, zone beams for covering less extensive areas and spot beams for covering smaller limited areas like a country or a group of countries. The only communication satellites that are not geostationary are the USSR's Molniya satellites which have highly elliptical inclined orbits to serve the communication needs of the USSR's extreme northern regions. Communication satellites were the first type of satellites to be used operationally for providing routine services and to achieve commercial viability. They are routinely being used for telephone, telex, telefax, television and radio transmissions, data/information exchange, teleconferencing, etc. In fact, they are now an integral part of the global telecommunication network.1/

The largest international satellite communication network is the International Telecommunications Satellite Organization (INTELSAT) system owned by an international consortium that links as many as 160 countries of the world. There have been successive series of INTELSAT satellites since the 1960s, with each new series or generation being more sophisticated than its predecessor. The latest INTELSAT V-A series occupies several slots above the equator over the Atlantic, Pacific and Indian Oceans. INTELSAT mainly makes use of the L, C and Ku Bands for communicating with earth stations. The USSR and its associated countries have their own satellite communication network called International System and Organization of Space Communications (INTERSPUTNIK) based on the Gorizont and Raduga satellite systems. Another satellite consortium named International Maritime Satellite Organization (INMARSAT) provides satellite based services for maritime communications and navigation. They have currently leased transponders on INTELSAT satellites as well as ESA satellites to provide communication links between coastal stations and ships for voice and video data, navigational data, weather data and distress signals.1/

Some advanced countries (e.g. Canada, Federal Republic of Germany, France, United Kingdom and United States) and a few developing countries (e.g. Brazil, India, Indonesia and Mexico) have their own national satellite communication systems for domestic use. There are also some regional satellite communication systems jointly operated and used by a group of countries, such as the ARABSAT that provides communication services among the Arab countries.

The second type of space information systems is represented by the meteorological satellites, some of which have been operational for many years. These satellites can either be geostationary like ESA's METEOSAT, India's Indian National Satellite (INSAT) 1-B, Japan's Geostationary Meteorological Satellite (GMS) (Himawari) and United States Geostationary

Operational Environmental Satellite (GOES); or polar orbiting, at about 800 to 900 km altitudes, like the United States NOAA series and the Soviet Union's Meteor satellites. These satellites provide global repetitive data on cloud cover, hurricane and storm build-up, atmospheric temperature profiles, atmospheric constituent gases and related environmental information on various surface features and phenomena such as global sea-ice, snowcover, sea and land surface temperature, vegetation, etc. The NOAA and GOES satellites also have other sensors to study solar radiation and proton flux, vertical distribution of ozone as well as facilities for collection and relay of information from ground based data collection platforms and capabilities to assist in search and rescue missions. They can, therefore, be considered as multi-purpose satellites. Meteorological satellites are now being routinely used in the advanced countries for weather forecasting, which is vitally important in oceanographic and marine activities. NOAA satellites carry radiometers operating in the visible to thermal part of the electromagnetic spectrum. The visible/near infra-red (IR) bands are used for monitoring weather and surface phenomena and the thermal bands for estimating land/sea and cloud top temperatures. They also carry scatterometers using narrow discrete bands for atmospheric sounding.2/

Another important class of satellites are the dedicated systems for Earth resources surveying, which usually orbit at altitudes between 700 and 900 km. These include the well-known United States Landsat series which have been the main source of satellite remote sensing data of the Earth's land surface for the last 17 years. The multispectral scanner (MSS) on the Landsats 1-5 images the Earth in four spectral bands in the visible and near IR bands at a spatial resolution of 80 metres. The other sensor on the Landsats 4 and 5, the thematic mapper (TM), images the Earth in six bands covering the visible to middle IR region with a resolution of 30 metres and a thermal band with a resolution of 120 metres. The more recent French SPOT satellite launched in 1986 provides a high spatial resolution of 20 metres in three spectral bands in the visible to near IR region and a still higher spatial resolution of 10 metres in the panchromatic mode. There are other remote sensing satellites more oriented toward the study of the ocean and marine environment such as Japan's Marine Observation Satellite (MOS-1). The multi-spectral electronic self-scanning radiometer (MESSR) on board MOS-1 acquires data over the ocean and land surfaces in four spectral bands in the visible to near IR region with a 50 metre resolution. Another sensor, the visible and thermal infra-red Radiometer (VTIR) is being mainly used for measuring sea surface temperatures. The third sensor, the microwave scanning radiometer (MSR) is designed for measuring water vapour, rainfall, ice and snow. An earlier United States satellite, SEASAT that preceeded MOS-1 by nearly a decade, provided a very useful set of data on the oceans and coasts for a few months in 1978 before it developed a malfunction. Another United States satellite dedicated to the study of the oceans, the NIMBUS-7, carried, among several other sensors, a dedicated sensor called the coastal zone colour scanner (CZCS). CZCS also provided very valuable data on marine and ocean

phenomena and was particularly helpful in the identification of chlorophyll, phytoyplankton and areas potentially rich in biological activity. Another satellite that has great potential for physical oceanography is the United States Geosat. It uses radar altimetry data for the study of ocean surface topography, waves and winds.3/ Figure 1 shows some of the satellites discussed above in polar and geostationary orbits (not drawn to scale).

There are also a number of miscellaneous scientific satellites other than those being used for remote sensing and meteorology. These acquire data on a variety of phenomena and processes of interest to the scientific community. Examples are satellites like United States Magnetic Field Satellite (MAGSAT) for measurement of the Earth's magnetic field, the United States TRANSIT and NAVSTAR satellites for global positioning and geodetic studies and Earth Radiation Budget Satellite (ERBS) for measuring the Earth's incoming and outgoing radiation. Another United States series of satellites, called NIMBUS, has carried a variety of sensors for studying many diverse phenomena and processes of scientific interest. NIMBUS satellites have also been used to test the performance of various types of sensors before these are installed on other satellites for operational use.

With regard to reconnaissance satellites, it is well known that they provide the extremely high spatial resolutions necessary for the specific tasks for which they are launched. However, very little information on these is available and they also fall outside the purview of this paper.

OPPORTUNITIES OFFERED BY SPACE INFORMATION SYSTEMS

Satellite or space information systems play a vital role in the study of the oceanographic and marine environment. Due to the fact that the oceans and seas represent a huge expanse covering more than 70 per cent of the Earth's total surface area, satellites are ideal platforms for repetitively observing and monitoring the oceanic and marine environment. They can be important sources of information on physical oceanographic processes as well as on living and non-living marine resources. They can provide data on sea levels, ocean topography, wave heights, winds, sea surface temperatures, ocean circulation patters, upwelling areas, bathymetry, marine pollution and the coastal environment. As illustrated, Figure 2 shows the use of Seasat radar altimeter data for the study of ocean topography and circulation, and Figure 3 shows sea surface temperatures. Some of the parameters they measure can be useful in both marine biology and physical oceanography. For instance, sea surface temperature, which can be measured by satellites up to an accuracy of 1/2°K or better, is a useful indicator of nutrients and biological activity as well as an important element in ocean circulation studies. Figures 4 and 5 provide examples of the use of Nimbus-7 CZCS imagery to show differences in ocean colour for locating favourable fishing areas. With the sophisticated sensors and systems now available for remote sensing of the oceans, particularly microwave/radar devices, satellites will become increasingly important components of global oceanographic research programmes, such as the World Ocean Circulation Experiment (WOCE) and Tropical Ocean Global Atmosphere

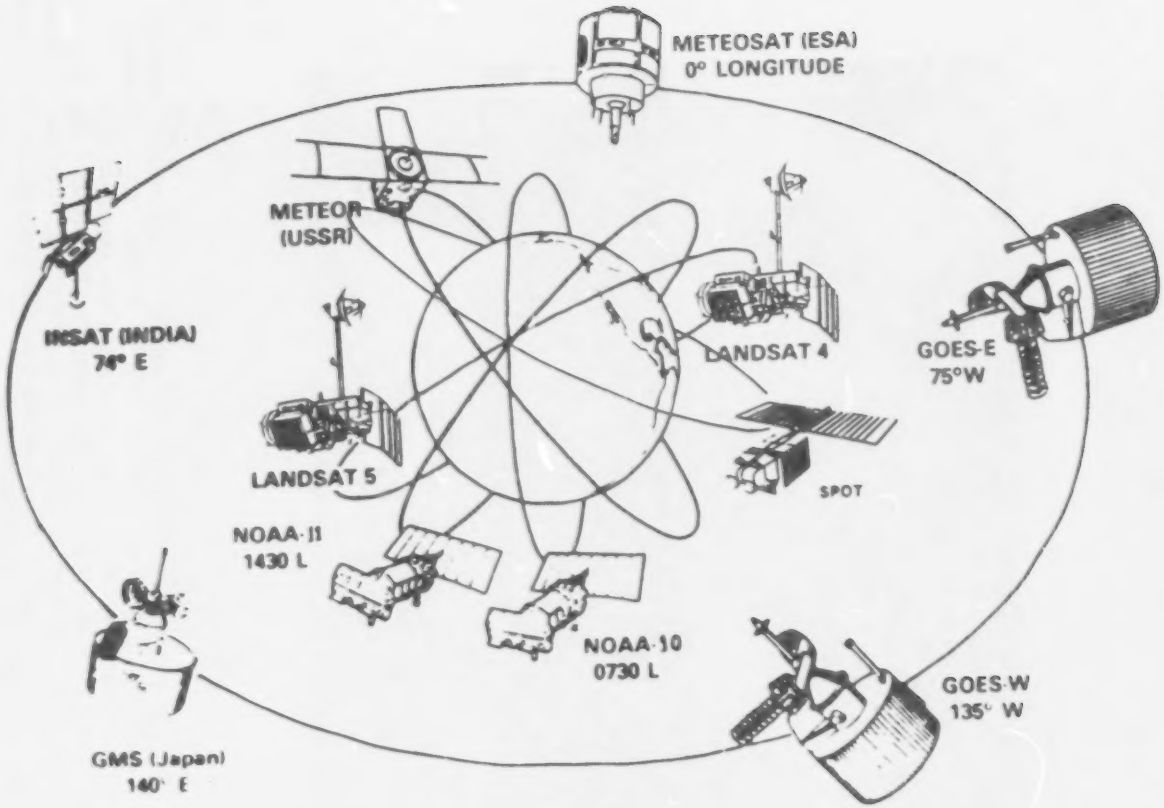

Figure 1 Some of the satellites mentioned in the paper shown in polar and geostationary orbits (not drawn to scale).

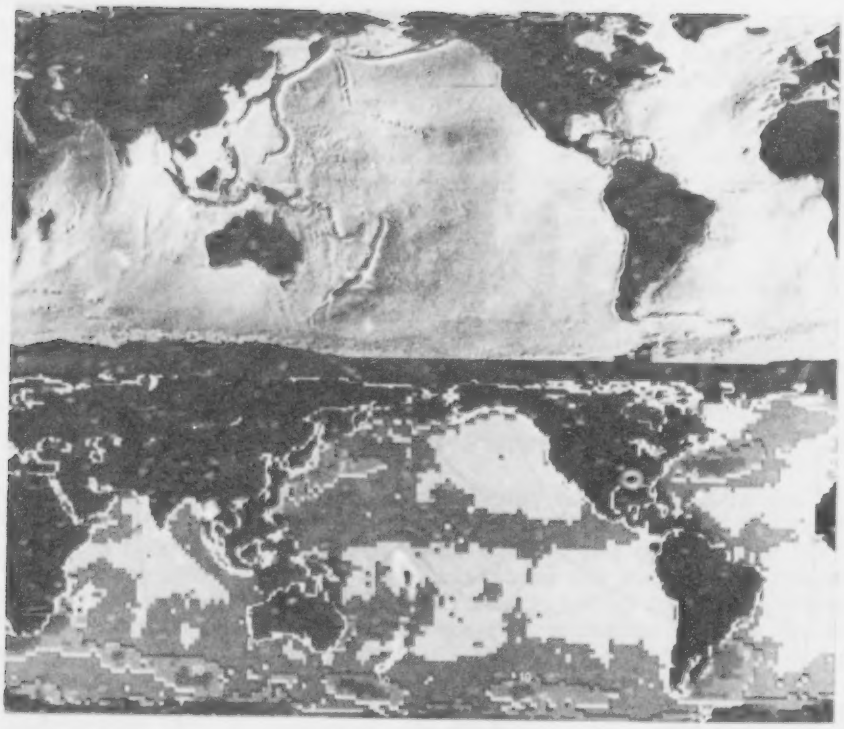

Figure 2 The top figure is a computer-generated global map of average sea surface topography derived from 70 days of Seasat radar altimeter data. The ocean surface has a relationship to the ocean-bottom topography; the characteristics of the ocean floor features can be located in the map. The bottom figure is a global map showing the mean variability in sea surface topography and the characteristics for a one month period, September to October 1978.

Figure 3 The distribution of sea surface temperatures (SST) in the Pacific Ocean derived from NOAA AVHRR data on two dates one year apart.

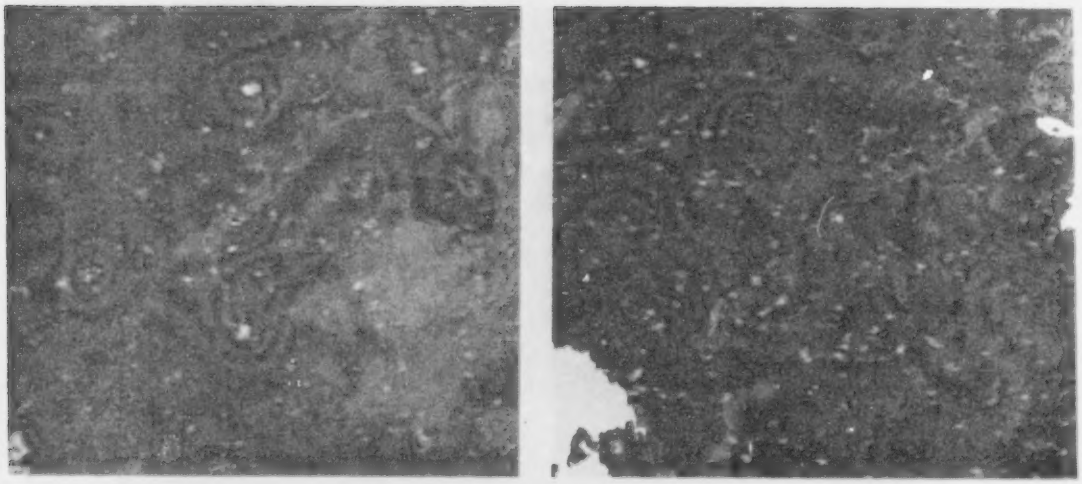

Figure 4 Satellite observations of sea surface temperature (left) and ocean colour (right) showing correspondence between physical oceanography and marine productivity.

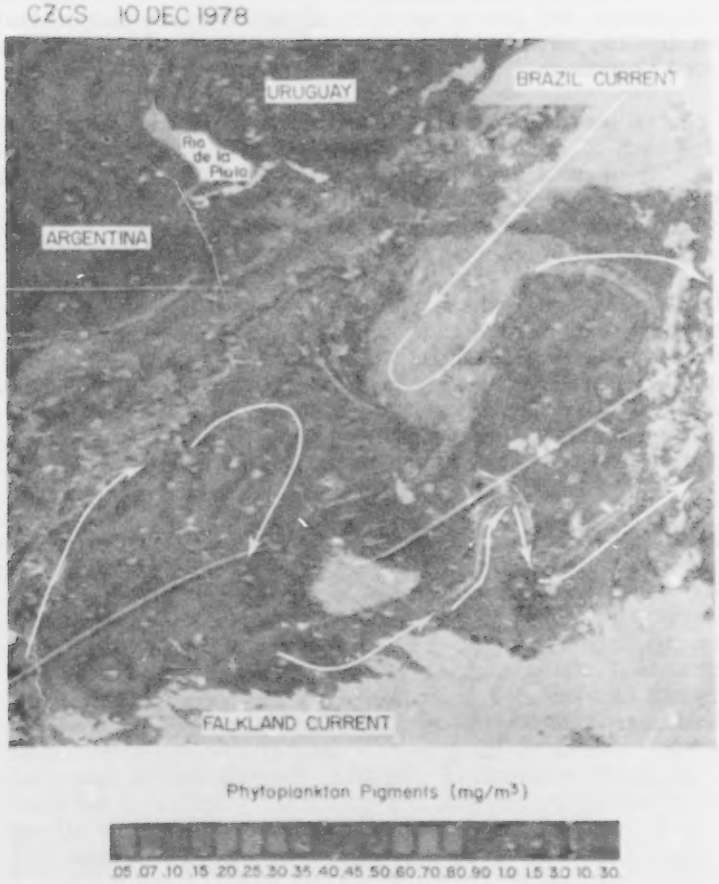
CZCS 10 DEC 1978
URUGUAY
BRAZIL CURRENT
Rio de la Plata
ARGENTINA
FALKLAND CURRENT
Phytoplankton Pigments (mg/m³)
.05 .07 .10 .15 .20 .25 .30 .35 .40 .45 .50 .60 .70 .80 .90 1.0 1.5 3.0 10. 30.

Figure 5 This CZCS image shows distribution of phytoplankton pigments associated with the confluence of two major currents systems in the Western South Atlantic.

(TOGA) carried out under the auspices of the World Meteorological Organization (WMO) and the International Council of Scientific Unions (ICSU).4/ WOCE, in particular, is an ambitious undertaking that will study a variety of oceanographic phenomena and processes such as sea surface temperatures, ocean topography, sea levels, wave heights, currents, tides, wind patterns, eddies and other related phenomena.

Already remote sensing satellites and meteorological satellites acquire and transmit a wealth of data for studying the Earth's atmosphere, land and ocean surfaces. These data have tremendously improved our understanding and knowledge of the Earth's atmosphere, Earth resources, global weather patterns, climatic changes, ocean dynamics, coastal processes, marine resources and environmental changes, etc. A few examples are given in figures 6 to 9. figure 6 is a typical NOAA APT image of Pakistan showing clouds, snow cover and other features. figure 7 shows the mangrove forests in the Indus delta in Pakistan mapped from SPOT data. figure 8 is a SPOT image of the Pakistan coast showing various geological/coastal features. figure 9 shows a Landsat image of the northern areas of Pakistan showing snow, glaciers, forests, barren mountains and other features. These examples show that the opportunities that satellites and other space-borne platforms offer for sensing and imaging the ocean surfaces globally and repetitively are indeed significant.

In addition to directly acquiring data over the Earth's oceans and land surfaces, satellites can perform the vitally important function of relaying and transmitting data and information collected on the ground, such as, for instance, through data collection platforms (DCPs). They are especially useful for relaying data from DCPs that are located in remote inaccessible area. Although satellites essentially sense the ocean surface, satellite remote sensing data can be used to make several references regarding sub-surface conditions. Nevertheless, the need for in situ measurements from ground surveys will always be there, at least, in the foreseeable future. On the seas, such in situ measurements are made through ships, moorings and buoys. Some of the buoys have DCPs for collecting data on various oceanic and meteorological parameters. These data are relayed, under the system, through the NOAA satellites to users directly or to a central reception facility in France, from where they are then retransmitted to users throughout the world using various communication links including the WMO's Global Telecommunication Service as shown in figure 10. There are also geostationary satellites like the Tracking Data Relay Satellite System (TDRSS) that relay information acquired by other satellites, such as when the Landsats operate outside the coverage zone of a receiving station to a central ground receiving facility in the United States for recording and processing.5/

ACCESS TO SPACE INFORMATION SYSTEMS

The opportunities that satellites offer are undoubtedly immense, as the above discussion has shown. The question, however, is how to grasp or make use of these opportunities. Before the data can be used they have to be first accessed by appropriate ground data reception facilities. Such facilities

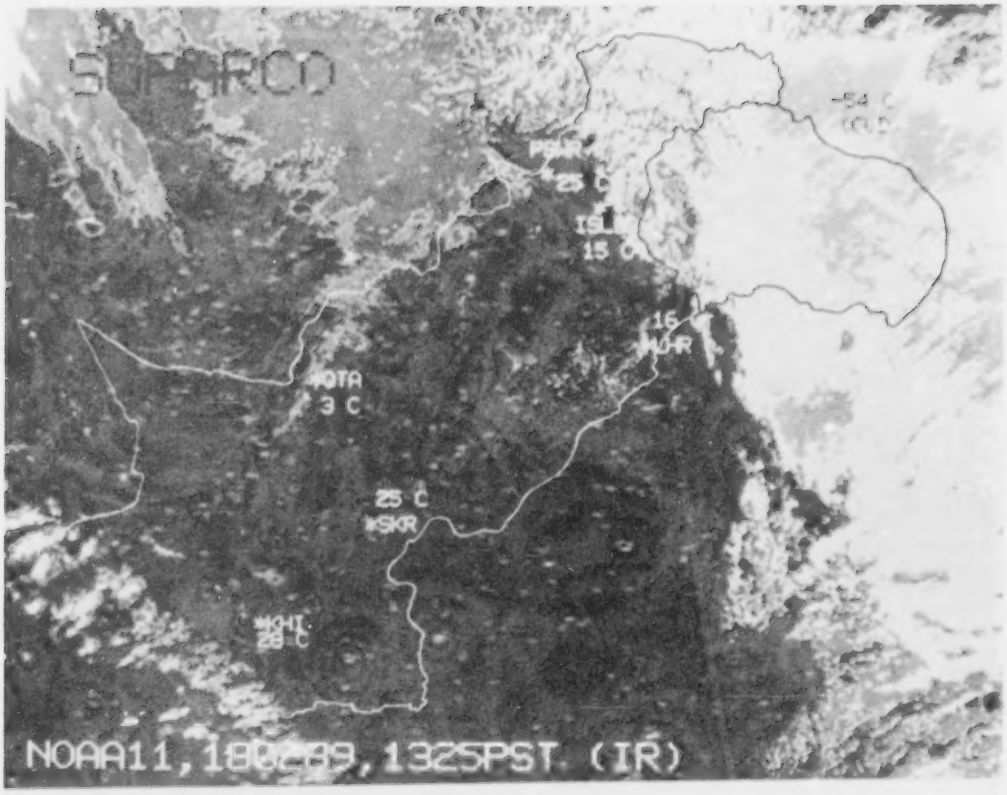

Figure 6 The NOAA automatic picture transmission (APT) infra-red image of Pakistan and surrounding areas acquired by SUPARCO APT station showing temperatures of cloud tops, clouds, snow, coastline and other ground features and their temperatures.

Figure 7 Mangrove forests in a part of the Indus delta along the Pakistan coast appear in red on this digitally enhanced SPOT colour composite.

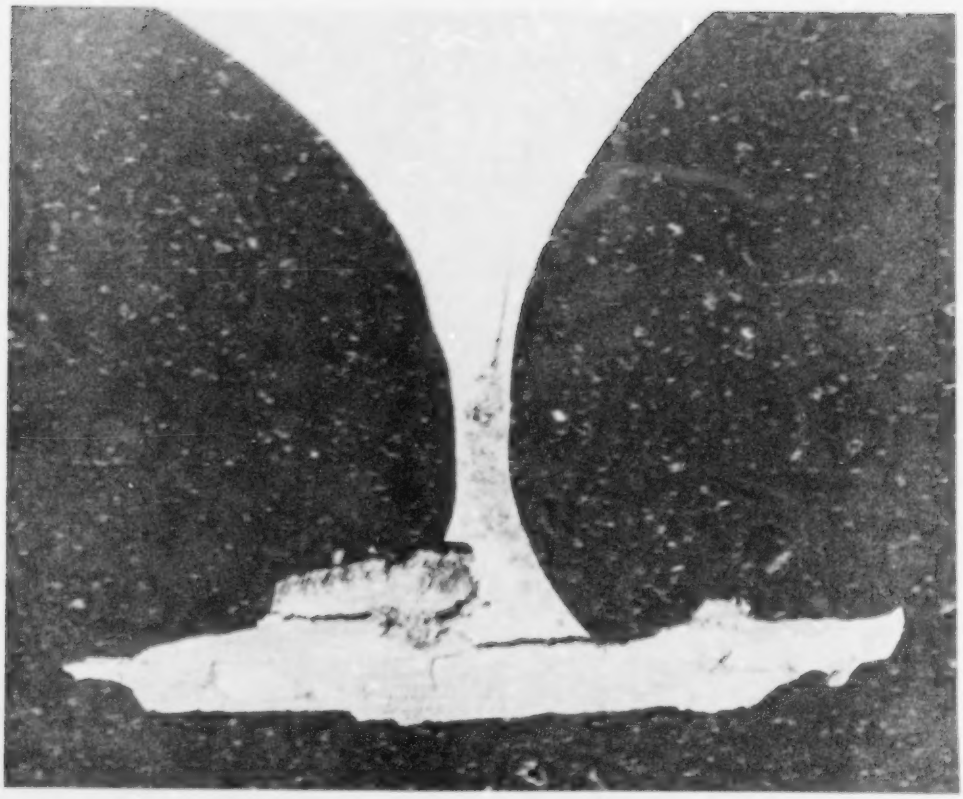

Figure 8 The rocky headland of Gwadar in Baluchistan on the Pakistan coast. The headland is connected to the mainland by a sandy neck. The beach zone is fringed by sand ridges.

Figure 9 A Landsat MSS colour composite of a part of northern Pakistan showing snow, glaciers, drainage patterns, forests and barren mountains.

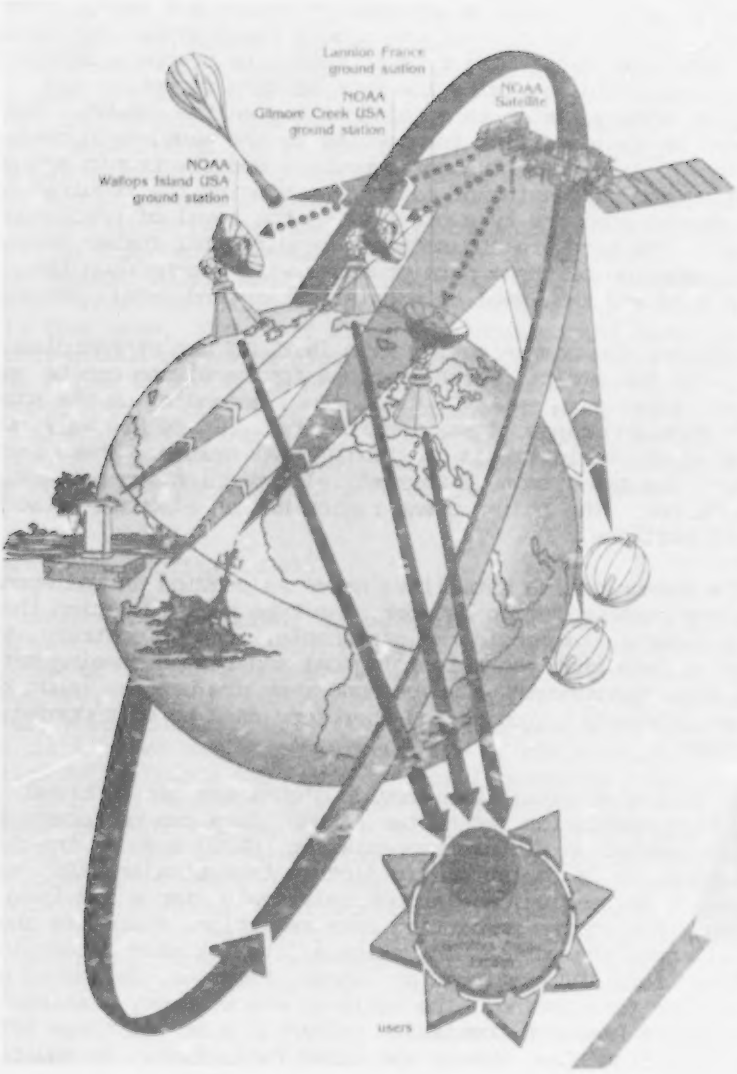

Figure 10 Data acquisition, transmission and relay through the ARGOS system.

must include tracking and receiving antennae to lock on to the frequencies being used by the various satellites for communicating with the ground and/or for transferring information, with associated electronic equipment for amplification of signals, noise suppression, demodulation and other necessary functions. In the case of remote sensing and meteorological satellites, this is followed by preprocessing/processing of the raw data into usable forms. Preprocessing entails various corrections, calibrations and reformatting operations that require sophisticated computers and electronic equipment. The next stage is concerned with the actual application of these data involving further processing and analysis/interpretation to extract useful information. This, in essence, is the function of any ground based system for reception and processing of satellite data. The type of satellite or space information system being tapped would determine the type of data reception and preprocessing/processing system to be established on the ground. The antenna size will depend on the down link frequencies or the wavelength bands used for the transmission of data. The type of computers and electronic equipment used for preprocessing and processing of data for producing the required end products will depend upon the type of data and the level of precision required. Again, the hardware and software required for futher processing and analysis/interpretation of these data products will depend upon the application in mind and the level of sophistication and detail desired.

Earth stations for communicating with INTELSAT use standardized equipment all over the world. Earth stations for receiving can be one of several distinct types such as A, B, C, Z, etc., depending on the satellite itself and the type and range of services desired. There are well over 700 Earth stations in the world linked to the INTELSAT system. These Earth stations connect the satelite to a terrestrial communication network of their respective countries. The Indian Ocean region has an adequate network of such satellite Earth stations.

While the communication satellites services provide an indispensable part of the global communication network, the type of information that they handle can, in general, be considered perishable. On the contrary, the type of information or data that the meteorological and remote sensing satellites handle have a more "permanent" value because they are used as input to resource and environmental studies and therefore need to be recorded or processed further.

The NOAA series of satellites provide global weather coverage. The NOAA advanced very high resolution radiometer (AVHRR) data can be accessed in either the high resolution picture transmission (HRPT) mode at the full 1.1 km spatial resolution, or in the automatic picture transmission (APT) mode at the degraded, coarse 4 km resolution, through relatively simple and inexpensive ground stations. For coarse resolution data reception, there are about 1,000 APT stations all over the world. In Pakistan, the Pakistan Meteorological Department offers four APT stations, at Lahore, Peshawar, Islamabad and Karachi for weather forecasting. The national space agency, Pakistan Space and Upper Atmosphere Research Commission (SUPARCO) also has three APT stations for accessing data from NOAA, Meteor and other facilities. In addition to this, SUPARCO has set up facilities at its Landsat/SPOT Ground Receiving

Station at Islamabad to receive 1.1 km NOAA AVHRR data. NOAA data can be accessed free of cost, i.e., without any payment of user fees to the satellite operator. The NOAA system is, therefore, providing an invaluable service to the meteorological and scientific community all over the world. Likewise, the geostationary meteorological satellites continue to provide weather and environmental information with a high observational frequency.

Acquisition of data from remote sensing satellites requires much more sophisticated and advanced equipment. The data bit transmission rates are much higher and the data processing involved is more complex. Consequently, there are far fewer receiving stations for remote sensing satellites. However, the northern and eastern parts of the Indian Ocean region do have a fairly adequate network of Landsat ground receiving stations. Some of these have recently been upgraded to receive SPOT data as well. Receiving stations are operational in Australia, Thailand, India, China, Pakistan and Saudi Arabia. SUPARCO established the Pakistan station near Islamabad. It is equipped to acquire Landsat MSS/TM and SPOT high resolution visible (HRV) (multispectral and panchromatic modes) data as well as NOAA AVHRR HRPT. The Bangladesh station, which is reported to have been damaged by recent flooding in the country, is expected to become operational in due course. However, Africa and the western Indian Ocean region are not adequately covered by Landsat and SPOT receiving stations. Only the South African station is fully operational in that area. figure 11 shows the location and coverage zones of the Landsat/SPOT ground receiving stations in the Indian Ocean region. Currently, the Indian Ocean region has two stations for the reception of data from the Japanese MOS-1. One is in Australia and the other is in Thailand. The MOS-1 ground stations in Japan do not cover any significant part of the Indian Ocean region. However, the MOS-1 ground station in Antarctica provides some coverage of the extreme southern part of the Indian Ocean.

PROBLEMS IN ACCESSING SATELLITE DATA

For the developing countries, the establishment and operation of ground receiving stations for remote sensing satellites is a difficult proposition. The sophisticated technology required is, in most cases, only available from outside the country, entailing expenditure of valuable foreign exchange. In these countries, where the usually meagre financial resources have to be thinly spread out over so many essential sectors of the economy, it is not easy to mobilize and allocate the large financial resources required for the establishment of ground receiving stations. In addition, the very heavy user/access fees now being charged by the satellite operators have made it increasingly difficult for the developing countries to operate and run such stations. In fact, it is feared that such heavy access fees and the resultant high cost of the data products would undoubtedly inhibit, rather than promote, the use of satellite remote sensing technology in the developing world where the need for resource information and mapping is far more urgent than it is in the developed world. Other factors that constrain and restrict the

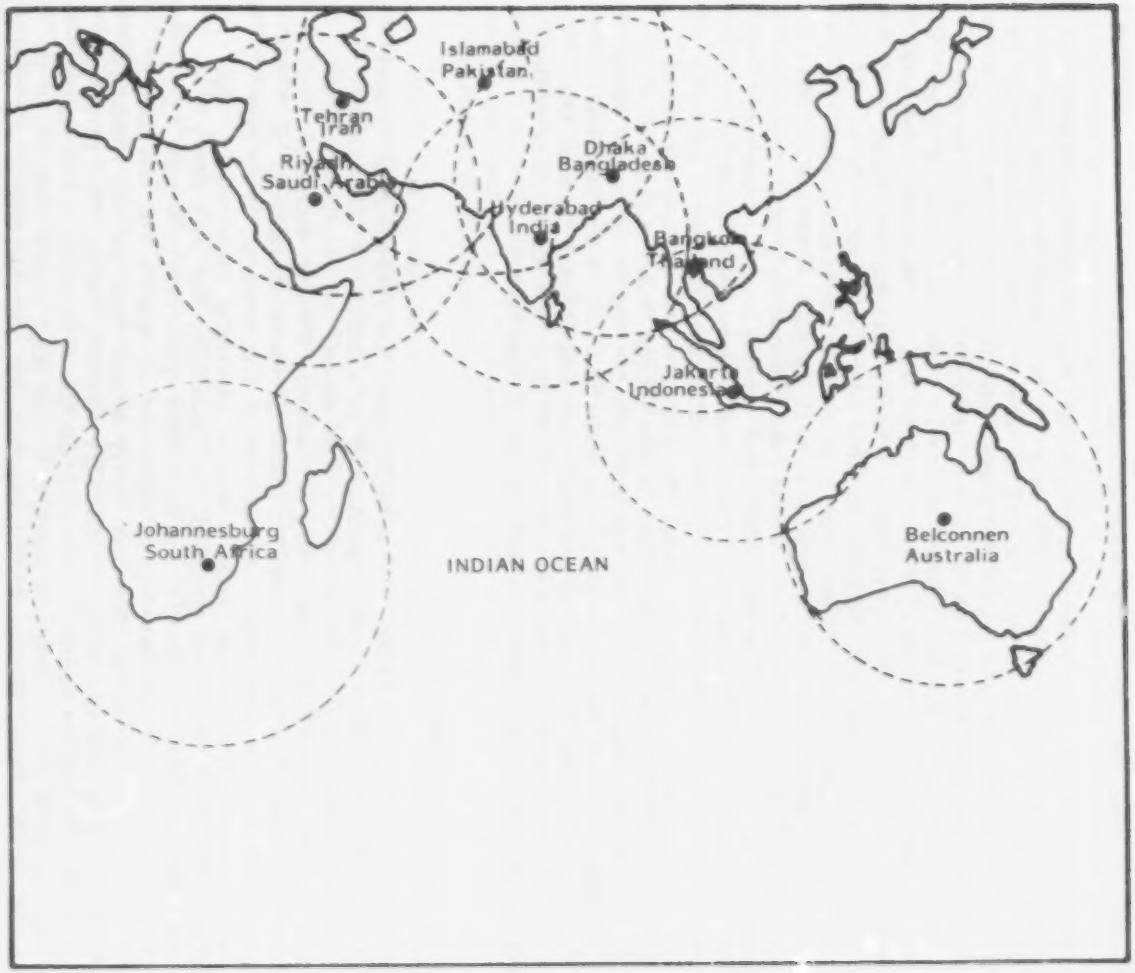

Figure 11 The location and coverage zones of the various Landsat/ SPOT receiving stations in the Indian Ocean Region.

establishment of such facilities is the lack of sufficient manpower and expertise for operating and maintaining the sophisticated equipment. Also, the relative paucity of scientific research programmes and the lack of know-how and facilities limit the use of these data for various applications in the developing countries. A number of technological, financial, manpower and logistic problems, therefore, have to be encountered by the developing countries in the establishment and operation of ground receiving stations. The situation is further worsened by the fact that satellites like Landsats 4/5 and MOS-1 do not have on-board tape-recorders so that data of areas outside the coverage zones of existing ground receiving stations cannot be acquired. Even the TDRS system is not able to ensure full global coverage and there is a large "zone of exclusion" which unfortunately includes substantial parts of Pakistan that Landsats cannot image except through a ground station. This was, in fact, one of the principal reasons that prompted SUPARCO to set up a ground receiving facility for Landsat/SPOT within the country itself.

The coverage zone of a receiving station often includes several countries. The flow of data from the station to users in foreign countries may not always be timely or regular because of the data acquisition and processing priorities of the country in which the facility is located. Even within a large country, there are sometimes delays in supply and dissemination of data to the ultimate user owing to a backlog of orders. The last stage in data dissemination from the receiving station to the user is crucial and the time-lag ought to be reduced if satellite remote sensing data are to be used in the real, operational sense. Data dissemination mechanisms must be streamlined so that the data products are in the hands of the user within a reasonable time of their acquisition.

INFORMATION AND DATA EXCHANGE NETWORKS

Data can be exchanged in various ways using ordinary postal services, on-line access systems, satellite relay systems, etc. In the exchange of information, especially across national boundaries, the idea of regional/international networks is gaining ground. Many of the information/data exchange networks operating in Europe and North America make extensive use of satellites for relay of data. These networks have expanded and developed over the years and employ computerized and structured databases and satellite-based data relay systems. The Global Telecommunication Service (GTS) of WMO is providing useful service in the distribution of data to meteorologists all over the world. As stated earlier, GTS is being extensively used for the relay of data collected by DCPs under the system. There are several information networks catering to European needs such as SPINE, STELLA, SPAN, JANET, EARTHNET and IRS. EARTHNET and IRS are oriented toward acquisition, archiving, retrieval and dissemination of Earth observation data. Some of these networks are linked to similar networks in North America. IRS can also be accessed outside Europe wherever modems have been set up under arrangements with ESA. There are facilities in Pakistan that also are for access to the European IRS.

In the Indian Ocean region, as far as is known, no such sophisticated network exists. However, one example of a network being developed in the eastern Indian Ocean region is the Regional Information Service (RIS) of the Regional Remote Sensing Programme of the United Nations Economic and Social Commission for Asia and the Pacific (ESCAP). RIS is currently developing the necessary infrastructure and contacts among the various member countries. Inventories of remote sensing facilities and activities, rosters of professionals, lists of projects and bibliographies are being prepared on the basis of the information provided by member countries. Initially, small personal computer-based systems are being used for building the necessary databases. The RIS will eventually provide an effective medium for exchange of remote sensing data and information among the member countries. It would provide a significant boost to remote sensing application activities of the region. As far as is known, no corresponding regional network is operating in the western part of the Indian Ocean region covering Africa.

Another network being planned for space related activities is the Inter-Islamic Network for Space Science and Technology, under the auspices of the Organization of Islamic Conference (OIC). This would cover a significant part of the Indian Ocean region from Indonesia in the east to the Arab countries and the north-east African countries in the west and beyond to other middle eastern and north African countries. Pakistan has been designated as the co-ordinator for this programme. It is envisaged that a central data network located in Pakistan's SUPARCO will serve as a medium for exchange of information on activities and programmes related to space science and space technology, including satellite remote sensing.

THE FUTURE

Future programmes in the 1990s will witness the launch of several systems dedicated to oceanographic and marine applications. These include ESA's Earth Resource Satellite (ERS-1), the United States/French TOPEX/POSEIDON mission, Japan's Japanese Earth Resource Satellite (JERS-1) and ADEOS and Canada's RADARSAT. Other satellite systems important for oceanographic and marine applications are the GOES-Next series and the NOAA-Next series which would be improved versions of existing systems. It is also planned to install a sensor called SeaWifs for oceanic and marine applications on board the Landsat 6. A notable feature of many of these planned missions is the use of microwave/radar sensors, including synthetic aperture radar (SAR), that would provide all weather coverage and would, therefore, be especially useful for observing the oceans where cloud cover is often present. There is a need to develop techniques and expertise for the processing and analysis of microwave/radar image data. Toward the turn of the century, ESA, Japan, the Soviet Union and the United States will launch space stations and polar orbiter platforms that will provide composite systems carrying a variety of optical, near and middle IR, thermal IR, passive microwave and active radar imaging devices. These systems, that will be launched in the next decade, will support advanced global climatic/ oceanographic programmes that are expected to increase understanding of our planet Earth enormously.

CONCLUSION

There is obviously a great need to strengthen the ground segment, in terms of data acquisition and processing capabilities as well as data dissemination and distribution procedures. Effective mechanisms and networks will have to be developed both nationally and internationally in order that the requisite data reach the end user in time. This is necessary to ensure that the data can be used in a fully operational manner. It is also important that these data and services are available at prices that the developing countries can afford so that their use can also be cost-effective. Operational use without cost-effectiveness has little meaning particularly for the developing world.

NOTES

1/ Mark Long, World Satellite Almanac: The Complete Guide to Satellite Transmission and Technology.

2 / ESA, Annual Report, 1987.

3/ A. Schnapf, The Operational Environmental Satellite of the 80s, COSPAR Proceedings, 1986

4/ World Climate Research Programme, WMO/TD, No. 241, 1988.

5/ World Climate Research Programme, vols. I & II WCRP-11, 12 WMO/TD No. 242, 243.

INTERNATIONAL CO-OPERATION IN THE ACQUISITION AND DISSEMINATION OF SATELLITE REMOTE SENSING DATA

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INTRODUCTION

Remote sensing came to the attention of the United Nations shortly after the launch of the first Landsat satellite in 1972. Because remote sensing satellites have an inherent capability to cover the entire Earth, it was clear that the question of international co-operation in the acquisition and dissemination of satellite data would arise.

In 1974, the United Nations Committee on the Peaceful Uses of Outer Space began discussions on principles to govern international remote sensing, but the negotiations soon ran into problems relating to sovereignty over natural resources and information concerning those resources. In general, developed countries called for an open system of acquisition and dissemination of data, while developing countries called for assurances that they would have control over access to information concerning their natural resources. In the 1980s, trends toward the commercialization of satellite remote sensing and concerns over possible exclusive access to economically valuable data by private companies complicated the issue.1/

In 1986, in the context of generally improving international relations, an agreement was reached, and the Committee on the Peaceful Uses of Outer Space and the General Assembly approved a set of "Principles relating to remote sensing of the Earth from space." Among a variety of principles encouraging international co-operation in remote sensing, the most important element of the agreement was that no limitations were to be placed on the collection of remote sensing data, but that any data collected by one country over another had to be made available to the sensed country "on a non-discriminatory basis and on reasonable cost terms."2/

In the context of this agreement, it is interesting to consider the history, present status and developmental trends in the international acquisition and dissemination of satellite remote sensing data.

Paper presented at the Fourteenth United Nations/Food and Agricultural Organization International Training Course on Remote Sensing Applications to Land Resources, Rome, 6-24 November 1989.

THE LANDSAT PROGRAMME

In 1972, the United States launched Landsat 1, the first satellite to provide remote sensing data regularly. The United States policy for Landsat was to acquire data for the entire land surface of the world and to make all data available to anyone who wished to purchase the data at highly subsidized prices ranging from $2 for a 1:1,000,000 scale black and white print to $80 for a larger scale colour composite and $200 for a computer tape. These prices covered only the cost of the materials used for reproduction. Landsat 1 was followed, later in the 1970s, by the almost identical Landsats 2 and 3, accompanied by modest price increases, maintaining continuity of service and encouraging users to integrate satellite data into operational resource management programmes.

In the 1980s, the situation began to change when the United States announced its intention to commercialize the system by transferring it to private industry and increasing prices to cover the cost of operating and maintaining the ground system and eventually for operating and maintaining the satellite system as well. Landsats 4 and 5 were launched with the higher resolution (30m) thematic mapper sensor in addition to the original multi-spectral scanner (80m) to provide continuous and improved data. In 1985, Landsat operations and data distribution were transferred to the Earth Observation Satellite Company, known as EOSAT Corporation, and as of January 1989, prices had increased to $350 for a 1:1,000,000 scale colour print and $3,600 for a TM computer tape.

Even at that level, however, revenues from the sales of data were far from adequate for covering system costs. Revenues were running about $20 million per year, while the total cost of operating the system and building further satellites to ensure continuity runs to about $100 million to $200 million per year. The prospects for making the system self-supporting through further increases in prices are not good because the price increases since 1982 have resulted in a substantial decrease in the number of products ordered. United States Government subsidies are therefore needed to keep the system going, but the Government is increasingly reluctant to provide the funding. In March 1989, Landsat satellite and ground operations were shut down until the government provided funding to keep the system going for the rest of the year. Long-term funding for operations and for building and launching Landsat 6 to replace the aging Landsats 4 and 5 is still not assured.

The Landsat system includes not only the satellites and the United States ground facilities, but also a growing number of foreign-owned and operated ground receiving stations and processing and distributing centres including facilities in Argentina, Australia, Bangladesh, Brazil, Canada, the Canary Islands, China, India, Indonesia, Italy, Japan, Pakistan, Saudi Arabia, South Africa, Sweden and Thailand. According to the agreements with EOSAT giving the countries the right to receive data from the satellites, the countries may set their own prices and agree to supply data to anyone within the coverage area of the ground station on a non-discriminatory basis. These ground stations originally did not pay for access to the satellite, but an annual fee was subsequently applied, now amounting to $650,000 per ground station per year. In addition, EOSAT charges a royalty fee for each product

sold, ranging from $5 to $300 depending on the product. Like the Landsat system as a whole, these ground stations are not self-supporting, but depend on government subsidies. A typical remote sensing satellite ground station will cost about $15 million in capital investment and perhaps $2 million a year in operating costs, and may generate revenues of half a million to a million dollars per year.3/

THE SPOT SYSTEM

Competition to the Landsat system emerged in 1986 with the launch of the first SPOT satellite by France. SPOT had a higher resolution than Landsat (20m for colour, 10m for black and white), but less spectral information (3 bands, versus 7 bands for the thematic mapper). Spot 1 will be followed by Spot 2, scheduled for launch in early 1990, and Spots 3, 4 and 5, which are intended to provide continuity of data through the 1990s. SPOT data, sold through the commercial agency SPOT Image, are somewhat more expensive than Landsat data, with product prices ranging from $1,300 to $2,800. The total revenue is comparable to that of Landsat, about $15 million per year. The SPOT system, like the Landsat system, costs about $150 million a year to operate and maintain the entire system.

In addition to the primary SPOT ground station in France, many of the Landsat ground stations have been adapted to receive SPOT data, including stations in Canada, Sweden, India, Brazil, Thailand,the Canary Islands and Pakistan. SPOT receiving capability is also planned for stations in South Africa, Saudi Arabia, Australia, Israel, China, Argentina and Bangladesh. These foreign ground stations pay an access fee to SPOT Image, a fee that is negotiated based on the number of images the country wishes to receive. The typical fee appears to be on the order of a few hundred dollars per image. Although SPOT data, like Landsat data, have copyright protection and cannot be reproduced without permission, SPOT will sell reproduction rights for a negotiated fee. It should be noted that assessing ground station fees on the basis of the number of images received strongly discourages the systematic collection and archiving of data for possible future use.

THE SOVIET SYSTEM

The Soviet Union has long operated a variety of satellites with remote sensing capability, including the manned space stations Salyut and Mir, the unmanned film-return satellites in the Cosmos series and electronic systems that transmit images to ground receiving stations. Until recently, the Soviet Union provided data only to countries with which it had major co-operative remote sensing projects, including the Eastern European countries, Cuba, Viet Nam, Mongolia and the Syrian Arab Republic, among others. Apparently, there were no defined prices for the remote sensing products.

More recently, the Soviet Union has offered to sell satellite data more widely at defined prices. Data is available from the MKF-6 70 mm multiband camera and the KATE and KFA-1000 large format cameras. These cameras take photographs from an altitude of 250 km, with 60 per cent overlap for stereo,

and return the film to the ground for processing. The original film images have scales between 1:200,000 and 1:2,500,000, with resolutions between 5 m and 60 m, and covering areas from 65 km square to 300 km square. Prices for these products range from $100 for small format black and white images to $1,000 for larger format colour images. They are distributed by Soyuzkarta, which does not publish a catalogue of available data but will provide information on request concerning the acquisition of images.1/

THE INDIAN REMOTE SENSING SYSTEM

In 1988, India launched the Indian remote sensing (IRS) satellite carrying the linear imaging self-scanned sensors (LISS) providing four-channel multispectral data with either 36 m or 72 m resolution. Prices for these products distributed by the National Remote Sensing Agency in Hyderabad range from $40 to $250, rather less than the prices of other systems for comparable products. It appears that the Indian Government is committed to launching further IRS satellites and to maintaining a substantial subsidy of system operation to encourage wide use of the data. Data have been made available to users in neighbouring countries within the 2,500 km range of the ground station in Hyderabad.

Currently, IRS data is received only by the Hyderabad ground station and hence the only foreign data available are for the immediately surrounding areas. India has indicated a willingness to consider direct access to IRS data by ground stations in other countries, but the terms for such reception have not been announced.1/

FUTURE CO-OPERATION IN REMOTE SENSING

A number of other remote sensing satellite systems are planned for the near future, with data to be internationally available. In 1991 and 1992, ESA's ERS-1 satellite and Japanese JERS-1 are scheduled for launch, and in 1994, Canada is planning to launch the Radarsat system. These three satellites carry microwave imaging radars which produce images quite different in nature from the multispectral images of existing remote sensing satellites. While the microwave data will have important new applications to oceanography, they will also be useful for land resource mapping, including the measurement of new parameters such as soil moisture and soil texture. While some conventional image interpretation techniques will be applicable to the new data, new techniques will be needed in other respects. Plans are being developed to make the data widely available.

In addition, Brazil and China have announced plans for a joint project, with Brazil taking responsibility for the satellite and China providing the launching, scheduled for 1992. Plans concerning the international availability of data have not yet been announced.

INTERNATIONAL ACCESS TO REMOTE SENSING DATA

The proliferation of remote sensing satellite systems ensures that data from a number of sources will be available for at least the next 10 years.

The future development of data prices is less certain; further price increases seem likely given the continuing pressure to make systems as self-supporting as possible, but the potential for increasing income by increasing prices is limited by the decline in demand as prices climb.

In the longer term, economic pressures are likely to push countries toward joint systems. In fact, in late 1988 and early 1989, in the context of the reluctance of the United States Government to assure financial support for the Landsat system, the United States and French government agencies responsible for the Landsat and SPOT systems discussed the possibility of merging the two systems in the future, but those discussions ended without any final decision. In any case, the best prospects for improving the economic viability of satellite remote sensing and for limiting further price increases would seem to lie in a small number of co-operative international systems, resulting in a gradual growth in demand for data and decreasing government subsidies. Given the sensitivity of demand to price, it is clear that the only hope for full commercialization lies in a large increase in demand, and that is not going to occur quickly at the present level of prices.

The current prices for remote sensing data pose major difficulties for users in developing countries, both because of the magnitude of the prices and the difficulties in obtaining foreign exchange, factors that severely limit the application of remote sensing in many countries. There are two ways in which these problems are being addressed.

The best solution is for each country to establish a national archive of satellite data. This, of course, still requires a substantial expenditure of foreign exchange, but can perhaps simplify the process of obtaining the necessary funds and can also maximize the benefits that can be realized from a given expenditure. The images could be loaned for use by different agencies, or, with an archive in the form of black and white negatives and colour transparencies, could be reproduced for users by a modest photo lab. A number of national and regional remote sensing centres, including the regional centres in Ouagadougou and Nairobi, have established substantial archives of data for their regions and can reproduce the data for users.

A second approach is to obtain data through technical assistance projects with developed countries with remote sensing programmes or with international organizations with expertise in the field. It appears that most developing countries without ground stations now obtain new data in this way. In particular, substantial bilateral assistance in remote sensing has been provided through the United States Agency for International Development (USAID), which provides about $6 million a year in support for space applications, as well as through technical assistance agencies in Canada, France and the European Communities. The United Nations Development Programme (UNDP), the World Bank, the Food and Agricultural Organization (FAO) of the United Nations and the United Nations Department of Technical Co-operation for Development also provide support for remote sensing activities in developing countries.3/

CONCLUSIONS

The policies of commercializing satellite remote sensing and the consequent price increases clearly limit the use of remote sensing, especially in developing countries. On the other hand, it would appear that purchases of data by developing countries contribute very little to the economic support of the satellite systems. Because the costs of satellite systems are independent of the number of users, and because the number of users is being substantially reduced by commercialization policies, it seems clear that these policies are reducing the benefit-to-cost ratios of satellite remote sensing.

The ideal solution to this problem, from the point of view of remote sensing users, is to treat remote sensing as a public service, just as satellite meteorology is treated. Thus, public expenditures should cover the large fixed costs of building and operating satellites and ground stations, ideally on a co-operative international basis, with maximum use of the data encouraged through the sales of the data at the cost of reproduction, thereby maximizing the benefit-to-cost ratio.

An alternative solution, if Governments insist on maximizing the direct return on their investment, would be to develop a differentiated pricing system, with special prices for groups that are likely to be excluded from the market by high prices. Clearly, no one benefits when potentially valuable data are not purchased due to limited resources. While conventional commercial operations may find it difficult to develop a differentiated pricing system, a modest amount of imagination and good will should be able to meet the challenge.

NOTES

1/ International Journal of Remote Sensing, vol. 10, No. 2 (February 1989), London, Taylor and Francis. This special issue of the Journal is devoted to papers on the commercialization of remote sensing," and includes papers on current developments in the remote sensing programmes of the United States, France, the USSR, ESA, Japan and India.

2/ Space activities of the United Nations and international organizations (United Nations document A/AC.105/358), New York, 1986. This document reviews the space-related programmes of the United Nations, the specialized agencies of the United Nations system including FAO and the United Nations Environment Programme (UNEP), intergovernmental organizations including ESA, and non-governmental organizations including the Committee on Space Research and International Astronautical Federation. It also contains the texts of the international legal agreements relating to space documents including the 19[illegible] Outer Space Treaty and a bibliography of United Nations remote sensing of the Earth from space. The Principle relating to Remote Sensing of the Earth from Outer Space, which had not been adopted at the time of publication of this document, are contained in the annex to United Nations General Assembly resolution A/41/65 of 3 December 1986.

3/ Further information on the Landsat programme is available from EOSAT, 4300 Forbes Boulevard, Lanham, MD 20706, USA.

OPERATIONAL SATELLITE ENVIRONMENTAL MONITORING FOR FOOD SECURITY BY FAO THE ARTEMIS SYSTEM

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ABSTRACT

Since 1976, the Remote Sensing Centre of FAO has, in co-operation with relevant FAO user divisions, actively been developing and testing the operational use of data from environmental and Earth resources satellites. Through the use of the data, it will be possible to improve the information bases of the FAO Global Information and Early Warning System (GIEWS) on food and agriculture and the desert locust plague Prevention Programme at international, regional and national levels.

This paper describes the operational satellite environmental monitoring system, ARTEMIS. FAO implemented this system in 1988, in co-operation with the National Aeronautics and Space Administration (NASA) Goddard Space Flight Center, of the United States, the National Aerospace Laboratory of the Netherlands and the Universities of Reading and Bristol in the United Kingdom, to provide information for real or near real-time precipitation and vegetation assessment in Africa, the Near East and south-west Asia, based on the integrated use of high frequency Meteosat and NOAA AVHRR data.

Furthermore, the paper summarizes the development status of the DIANA satellite telecommunication system of ESA. This system, formulated jointly by ESA and FAO, will permit near real-time transmission of high volume ARTEMIS digital data products to user terminals at regional and national levels in Africa.

This paper, presented at the United Nations/United Nations Development Programme/Food and Agricultural Organization/European Space Agency Meeting of Experts on Remote Sensing and Satellite Meteorology Applications to Marine Resources and Coastal Management, of Atlantic Coast of African region, Maspalomas, Canary Islands, Spain, 8-12 May 1989, does not necessarily represent the views of the United Nations.

INTRODUCTION

FAO's experience in using environmental and Earth resources satellite remote sensing data for assessment and monitoring of dynamic phenomena in the atmosphere and on the surface of the Earth, as they relate to the production and protection of food and animal feed, has, so far, been predominantly in the fields of food security and desert locust plague prevention. Since 1976, the FAO Remote Sensing Centre, in close co-operation with relevant FAO user divisions, NASA Goddard Space Flight Center (GSFC) and the Universities of Reading and Bristol in the United Kingdom, has been actively developing and testing the operational use of satellite remote sensing techniques for improving the information bases of the FAO Global Information and Early Warning System (GIEWS) on food and agriculture and the desert locust plague Prevention Programme.

This paper summarizes FAO's support of agricultural production and migratory pest monitoring and forecasting in Africa, the Near East and south-west Asia using the present state-of-the-art operational satellite remote sensing based precipitation and vegetation assessment. Furthermore, the paper describes the operational satellite remote sensing based environmental monitoring system, ARTEMIS, (Africa Real Time Environmental Monitoring Using Imaging Satellites), which became operational at the FAO Remote Sensing Centre in August 1988. The National Aerospace Laboratory of the Netherlands, in co-operation with NASA GSFC and the Universities of Reading and Bristol custom designed and built the ARTEMIS system for FAO.

The paper summarizes the development status of a dedicated satellite communication system for transmission of high volume ARTEMIS system and related products from FAO headquarters to users at regional and national levels, through the INTELSAT satellites. ESA and the FAO Remote Sensing Centre formulated jointly this dedicated satellite system, DIANA (Data and Information Available Now in Africa). DIANA is currently under industrial development for implementation on a demonstration basis with five remote terminal stations in Africa by mid-1990.

OPERATIONAL METEOSAT BASED RAINFALL ESTIMATION METHODOLOGIES

Rainfall estimation based on Meteosat secondary user station (SDUS) imagery

The FAO Remote Sensing Centre, in co-operation with the Remote Sensing Unit of the University of Bristol, has developed and implemented an operational methodology for qualitative precipitation monitoring of the African continent using Meteosat thermal infra-red (TIR) and visible (VIS) image data, recorded by a primary data user station (PDUS) that ESA provided on loan to FAO from November 1983 to March 1985.1/ A modified version of this method was formulated when the FAO Remote Sensing Centre installed a Meteosat Secondary Data User Station (SDUS) in November 1985. It uses a manual image analysis procedure, combined with computerized data processing and end user product generation for obtaining 10-day and monthly estimated rainfall images

for Africa on a one degree grid (approximately 100 x 100 km) as well as monthly rainfall anomaly maps, obtained by computerized comparison of the actual estimated monthly rainfall with the long-term mean monthly rainall, stored as digital reference maps in the computer system, in terms of percentage departures from normal rainfall.

The Meteosat SDUS data, apart from having degraded spatial and radiometric resolutions, are transmitted by the satellite as an analog signal and are therefore subject to fluctuations and, as such, cannot be used for numerical analysis of the data.

The operation of this methdology can be summarized as follows (Barret and Harrison, 1986):

- Acquisition of VIS/TIR Meteosat SDUS image coverage for the area of interest at an average frequency of three times/day (eight hour cycle);
- Application of a one degree grid on the image data and visual determination of the presence of precipitable cloud for each grid cell on the basis of the VIS/TIR image characteritics;
- Tabulation of observed grid cells with precipitable cloud on daily maps;
- Aggregation of daily maps into the 10-day "number of rainfall day maps";
- Entry of observed number of rainfall days for each grid cell into the computer according to a prescribed procedure;
- Multiplication by computer of the observed number of rainfall days with the mean rainfall/rainday statistical value for each grid cell and date;
- Computer generation of the 10-day "estimated rainfall map";
- Upon completion of three 10-day periods, computer aggregation of the three estimated rainfall 10-day totals for each grid cell;
- Computer generation of the "monthly estimated rainfall map";
- Computer calculation of the monthly rainfall anomaly map by determining the percentage departure, either positive or negative, from the long-term mean monthly rainfall for each grid cell;
- Computer generation of the "monthly estimated rainfall anomaly map".

FAO used this method on an operational basis for Africa as an input into GIEWS and the FAO Emergency Centre for Locust Operations (ECLO) from November 1985 to July 1988 when the ARTEMIS system became operational with an automated rainfall estimation procedure, based on the use of full resolution, high frequency digital Meteosat PDUS data.3/

The principal disadvantage of the SDUS based rainfall assessment procedure was that it was elaborate, and thus, limited the number of images/day that could be analysed with available manpower. Furthermore, by its nature, the method was subjective and therefore subject to human interpretation bias and variations. Thirdly, the rainfall estimates generated by this method represent a very coarse grid and could therefore be used only qualitatively in a general way.

Rainfall estimation based on Meteosat primary data user station (PDUS) data

The Meteosat primary data user stations (PDUS) receive data and transmit in digital format at full resolution (VIS: 2.5 km; TIR: 5 km) at 256 radiometric levels. The data allow for numerical data processing and development of automated rainfall estimation procedures.

In co-operation with the Tropical Agriculture Meteorology Satellite (TAMSAT) Project, Department of Meteorology, University of Reading, the FAO Remote Sensing Centre carried out a number of major Meteosat data acquisition and analysis programmes during 1986 and 1987. These programmes covered various regions of Africa and were used for the development, testing and calibration of a fully automated technique for precipitation estimation over large areas, based on high frequency (hourly) Meteosat TIR data, for future implementation on the FAO ARTEMIS system.4/ 5/

The TAMSAT methodology of rainfall estimation is based on a meteorological approach, i.e. assessment of precipitation from all precipitable clouds, using a high frequency of observation in the order of 24 times/day. The method distinguishes between a precipitable and non-precipitable cloud on the basis of the principle that the colder the cloudtop, observed in the thermal infra-red part of the spectrum by the satellite, the higher the chance of precipitation from a particular cloud. Research has established temperature levels varying generally between -60 at Saharan/Sahelian and -40 degrees centigrade at tropical latitudes to be the levels below which significant precipitation can be expected.

The TAMSAT Meteosat rainfall estimation method determines for each pixel over 10-day periods the duration of clouds which had a temperature below the above levels. This yields cold cloud duration (CCD) maps for which meteorological station locations have been correlated with observed rainfall for 10-day periods. On the basis of the relationships between the CCD values and for individual pixels and observed rainfall at stations located within those pixels, regressions have been established on the basis of which estimated rainfall can be determined for pixels not covering meteorological station locations.

In summary, the TAMSAT methodology for Meteosat based rainfall estimation, as implemented on the FAO ARTEMIS system, is being operated as follows:6/

- Automated acquisition of Meteosat digital TIR data on hourly basis through pre-programmed Meteosat PDUS reception schedule;

- At selected intervals, in the ARTEMIS system 2100 hours and 0400 hours automated transfer of available digital Meteosat images through ethernet link to central system computer (HP 1000 A900) for processing;

- Automated image selection for rainfall processing programme using predefined image quality control parameters;

- Computer mapping of selected images to ARTEMIS common geographic format, i.e. Hammer Aitoff equal area projection;

- Processing of available, in principle hourly, Meteosat images to determine cold cloud duration (CCD) for each pixel on the basis of time intervals between successive images, satellite calibration data and temperature thresholds for specific geographic regions: "daily cold cloud duration (CCD) images";

- Execution of DAYPRO for determination of number of raindays (NRFD) for 10-day periods and stores result in the ARTEMIS database;

- Execution of DECPRO which converts 10-day cold cloud duration (CCD) maps into 10-day estimated rainfall (ERF) maps using predetermined linear regression relationships; both CCD and ERF maps are stored in the ARTEMIS database;

- Execution of MNTPR which adds three 10-day maps (ERF and NRFD) and stores the created monthly map in the ARTEMIS database. Furthermore this programme compares the estimated monthly map in the ARTEMIS database. Furthermore this programme compares the estimated monthly rainfall maps with monthly long-term normal reference maps and generates relative and absolute monthly rainfall anomaly maps (MRFANABS/REL).

NOAA AVHRR BASED VEGETATION MONITORING TECHNIQUES

In 1978, NOAA of the United States launched the first satellite of the third generation polar orbiting environmental satellites, TIROS-N, followed by NOAA-6, NOAA-7, NOAA-8, NOAA-9 and NOAA-10 in the same series between 1979 and 1986. NOAA-11 was launched in April 1988.

The current NOAA satellites carry seven different sensor systems for observing the Earth and its atmosphere and two data collection/transmission systems.7/ Of the sensor systems, AVHRR has a multispectral capability similar to that of the Landsat and SPOT satellites. The AVHRR collects reflected and emitted electromagnetic radiation in five different spectral bands, i.e. the visible, near infra-red, middle infra-red and two thermal infra-red.

With the support from the Global Inventory, Modelling and Monitoring Systems (GIMMS) Group at NASA Goddard Space Flight Center, the FAO Remote Sensing Centre has developed and tested the use of AVHRR data for large-scale assessment of crop conditions and rangeland productivity and, in combination with Meteosat based rainfall assessments, for pinpointing of areas in the deserts of northern Africa, the Near East and south-west Asia which have suitable vegetation conditions for supporting the development of potentially dangerous desert locust populations.

For this purpose, NOAA AVHRR data are processed in a vegetation index format, using the following band combination:

$$\text{Normalized difference vegetation index (NDVI)} = \frac{\text{ch 2 - ch 1}}{\text{ch 2 + ch 1}}$$

The NOAA satellites provide effective world-wide data coverage every two to three days in the form of global area coverage (GAC) data which are produced through on-board resampling of the primary AVHRR data acquired by the satellite at full (1.1 km) resolution to a 4 km resolution. The full resolution data can be received directly by regional receiving stations in the form of high resolution picture transmission (HRPT) data. There is a limited capability for on-board recording of full resolution data and subsequent transmission to a ground receiving station in the United States in the form of local area coverage (LAC) data.

The relatively high temporal repeat frequency of the NOAA AVHRR data as compared to those generated by the Landsat and SPOT satellites allows for detection and monitoring of green vegetation dynamics, even in seasonally frequently cloud-covered areas. The NASA GIMMS Group has developed and successfully tested techniques for obtaining virtually cloud-free NOAA AVHRR NDVI data on a 10-day basis on a continental and even global scale.8/ 9/ This technique uses the daily available NOAA AVHRR data in the red, near infra-red and thermal infra-red channels. The thermal infra-red data is used to identify cloud covered areas. Data for 10-day periods are mapped to a selected geographic projection and cloud-free composite images are obtained for these periods by computer mapping of the cloud free parts by selecting pixels with the maximum NDVI, thus minimizing the effects of atmospheric influences as dust and haze.10/

The NOAA AVHRR data processing software as developed by the NASA GIMMS Group has been implemented on the ARTEMIS system by NLR and integrated with the Meteosat data processing software for mapping and database operations.

ARTEMIS SYSTEM CHARACTERISTICS

Hardware

The ARTEMIS system consists of a number of integrated hardware components, which are summarized as follows:11/

- A Meteosat primary data user station (PDUS) for direct reception of high frequency, full resolution digital Meteosat data in the visible, thermal infra-red and water vapour channels through a three metre dish antenna, down converter and receiver which has replaced the SDUS antenna/receiver being operated at the FAO Remote Sensing Centre for precipitation assessment in Africa. The ARTEMIS PDUS can also receive data from the GOES satellite, located over the Americas, which is relayed through Meteosat four times a day. The PDUS is controlled by a dedicated VME 68000 microprocessor. Received data are stored before thematic processing on two 150 Mb disks. The PDUS is operated from an operator console using menu-driven software and allowing data quality control through a quick-look display monitor;

- A computer unit consisting of a Hewlett-Packard 1000 A900 minicomputer, supported by a high speed 6250/1600 bps tape drive, two disks (132 and 571 Mb), a clock, a system console, a printer and a modem;

- An interactive image analysis workstation, consisting of a Ramtek interface to the HP 1000 A900 with a 1290 x 1024 x 16 bit display memory, a 19-inch high resolution colour monitor, a graphics terminal with touch screen capability, trackball and a printer;

- An output subsystem, consisting of a colour hard copy camera for 10 x 15 inch polaroid and 35 mm film products, an HP Vectra minicomputer for IBM personal computer and ERDAS compatible output on floppy disk and a six-pen colour plotter.

The ARTEMIS system hardware is currently being expanded with a multisync colour monitor and a matrix graphics card. This added capability will allow the operation of the Integrated Land and Water Information System (ILWIS) geographic information system software package that the International Institute of Aerospace Survey and Earth Sciences in the Netherlands developed.12/

ARTEMIS remote terminal connections within FAO Headquarters, through dedicated lines, linked to users microcomputers, are currently being established in GIEWS (ERDAS system), the Emergency Centre for Locust Operations (ECLO) (IBM PS 2 with VGA graphics) and the Centralized Geographic Information System (GIS) Group of FAO (ERDAS system). This will allow principal in-house user divisions directly to access the ARTEMIS database and transfer information products in digital formats to their own microcomputers for display and further processing in combination with data from other sources.

Two additional remote terminal ports to support other in-house users remain available on the present system configuration.

Software

The ARTEMIS system software can be divided into the following groups, according to function:11/ 3/

- Meteosat PDUS operating system and communications software for controlling data reception, quality control, quick-look display, temporary storage and transfer of data to the HP 100 A900 host computer for processing;

- HP 1000 A900 operating system software for operating the computer subsystem and related peripheral equipment;

- Application software for basic and thematic data processing and mapping Meteosat and NOAA AVHRR data into a common geographic format (Hammer Aitoff equal area projection) and for generation of output products in specific user formats;

- General applications software for data manipulation for operational and development purposes (NASA GIMMS software);

- Data base management and communications software for manipulation and integration of various ARTEMIS system databases with current data and for generation of the various output product formats;

- Sub-area and point data extraction software for definition and extraction of data for sub-areas and point locations from the ARTEMIS database.

ARTEMIS PRODUCTS

Operational products

As of 20 August 1988, the ARTEMIS system produces the following products on a routine basis:

- Ten-day cold cloud duration (CCD) maps for the continent of Africa and the Near East, based on hourly Meteosat data;

- Ten-day and monthly estimated rainfall (D/MERF) maps for the southern Sahara, Sahel, Sudanian and tropical countries of West Africa, obtained through regression relationships between CCD and ground observed rainfall;

- Ten-day and monthly estimated number of rainfall days (D/MNRFD) maps for Africa and the Near East;

- Ten-day and monthly NOAA composite vegetation index (D/MNDVI) maps for Africa, southern Europe, the Near East and south-west Asia.

All ARTEMIS products are available in a common geographic projection in either photographic or digital format at a spatial resolution of 7.6 km. All ARTEMIS digital images have a size of 2.6 Mb.

Experimental products

ARTEMIS products that have not yet been declared operational in view of further testing and/or development requirements, are the following:

- Crop moisture availability (CMA) maps, obtained by inputting DERF and DNRFD maps into a water balance calculation method which has been implemented on the system. This product can first be tested during the 1989 Sahel growing season;

- Potential breeding activity factor (PBAF) maps, obtained by combinations of the current DNDVI map with a potential desert locust habitat reference database on the system. This product is still under development and testing;

- Monthly rainfall anomaly (MRFANABS/REL) maps, expressed in absolute and relative terms, obtained by comparison of the MERF maps with the monthly rainfall normal reference maps on the system.

SATELLITE COMMUNICATIONS DEVELOPMENT: THE DIANA SYSTEM

Presently, the ARTEMIS system, located in Rome, serves primarily the environmental information needs of the GIEWS and ECLO of FAO, which communicate analysed information, combined from a number of sources, to recipient and donor countries in the form of telexed summaries and GIEWS and ECLO bulletins and publications. Rapid communication of the high volume ARTEMIS system information products, with the objective of serving a variety of users of such information at regional and national levels, requires special communication facilities.

Jointly with ESA, the FAO Remote Sensing Centre has formulated a project for the development, implementation and demonstration of the dedicated satellite communications system DIANA. The ESA Member States Italy, Spain, Belgium, Ireland, Norway and Finland approved the funding of approximately $7 million.

The DIANA system will provide the capability for high-speed, two-way transfer of facsimile images of documents and maps, character-coded text documents and digital images in raw or processed form from computers at FAO headquarters to personal computer based terminals of recipients. Initially DIANA will operate in Africa, using the commercial INTELSAT satellites through the facilities of Telespazio in Fucino, Italy. This allows the availability of ARTEMIS products in digital formats to users at virtually the same time that the system in Rome generates the information.

Furthermore, the DIANA system will facilitate improvements in current means of communications between FAO headquarters and the field for a variety of applications, including the communication of GIEWS and ECLO bulletins and related information both to and from the field.

The DIANA system is designed on a low-cost concept for the user. Initially, it is planned to implement the initial DIANA system on a demonstration basis for a period of one year with five remote terminal stations at selected locations in various regions of Africa. Locations of the remote DIANA terminal stations are:

- Nairobi, Kenya: Regional Centre for Services in Surveying, Mapping and Remote Sensing (RCSSMRS), location of FAO remote sensing/early warning project for the Intergovernmental Authority for Drought and Development region;

- Niamey, Niger: Centre AGRHYMET, responsible for crop forecasting/early warning programme of the Permanent Inter-State Committee on Drought Control in the Sahel region;

- Harare, Zimbabwe: National Meteorological Department, Location of FAO Remote Sensing/Early Warning Project for Southern African Development Co-ordination Conference region;

- Algiers, Algeria: National Meteorological Service, providing support to North-west Africa Desert Locust Commission (Algeria, Libyan Arab Jamahirya, Morocco, Tunisia)

NOTES

1/ Kalensky, Z.D. et al., Agricultural Drought Monitoring by Meteosat in Africa, Remote Sensing Series 37, (FAO, Rome, Italy, 1985).

2/ Barrett, E.C. and Harrison, A.R., Rainfall Monitoring by Meteosat in Africa, Consultants report GCP/INT/432/NET, (FAO, Rome, Italy, 1986).

3/ Hielkema, J.U., et al., "The FAO/NASA/NLR ARTEMIS SYSTEM: An Integrated Concept for Environmental Monitoring by Satellite in support of Food/Feed Security and Desert Locust Surveillance", Proceedings of the 20th ERIM Symposium on Remote Sensing of Environment", Nairobi, Kenya, Dec. 1986.

4/ Hielkema, J.U., et al., Operational Rainfall Monitoring in Africa Using Low Resolution Meteosat Observations, Proceedings of the 6th Meteosat Scientific Users Meeting, Amsterdam, Netherlands, Nov. 1986.

5/ Milford, J.R. and Dugdale, G., Rainfall Mapping over West Africa in 1986, 87, Consultants report GCP/INT/432/NET, (FAO, Rome, Italy, 1987).

6/ Van Ingen Schenau, H.A. et al., ARTEMIS System Overview and Presentation of ARTEMIS Products, ITC/FAO Seminar, 14-25 Nov. 1988, Enschede, Netherlands (1988).

7/ Kidwell, K.B., NOAA Polar Orbiter User's Guide, NOAA National Climate Centre, Washington, D.C., (1984)

8/ Tucker, C.J. et al., "Monitoring the Grasslands of the Sahel in 1984-85", Int. Journal of Remote Sensing, vol. 7, No. 11, (1986).

9/ Justice, C.O., ed., Monitoring of Grasslands of Semi-arid Africa using NOAA AVHRR Data, Int. Journal of Remote Sensing, vol. 7, No. 11, (1986).

10/ Holben, B.N., Characteristics of Maximum-Value Composite Images from Temporal AVHRR Data, Int. Journal of Remote Sensing, vol. 7, No. 11, (1986).

11/ Van Ingen Schenau, H.A. et al, System Definition of "Africa Real Time Environmental Monitoring Using Imaging Satellites" (ARTEMIS), National Aerospace Laboratory of the Netherlands (NLR), (1986).

12/ Meijerink, A.M.J. et al., "ILWIS: The Integrated Land and Watershed Management Information System", ITC Publication No. 7, (ITC, Enschede, Netherlands, 1988).

GEOLOGICAL-GEOMORPHOLOGICAL STUDY OF MODERN TECTONIC MOVEMENTS

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ABSTRACT

In studying, and especially in interpreting, modern movements of the Earth's crust, one should take into account its tectonic variability, its layering and the deformations exposed at the Earth's surface, which reflect the evolution of deep processes. No less important is the solution of the opposite problem, i.e., the study of deep tectonic processes, using data on modern movements of the surface. In both cases, analysis of the distribution of types of movement and regions along (active) faults is essential. Active faults in Asia between 20° and 60°N are taken as examples.

Time and again, various authors have correlated instrumental data on modern movements of the Earth's crust, or rather the Earth's surface, with recent Quaternary and Holocene tectonic structures exposed at the surface, and have made it evident that this information is not sufficient for a complete understanding of the essence, general direction, nature and cause of such movements. The literature cites many examples of when instrumented data can be well correlated with young tectonic structures, but there are also quite a few examples where such correlations are impossible, and movements may be complicated and negatively associated with structures.

The relationships of the individual and general features of tectonic movements, as well as their ranking and subordination, are evidently of a crucial importance in the study of modern tectonic movements, their origin, mechanism and space-time peculiarities. This problem is to be clarified further. We can assume that individual movements (recorded instrumentally and limited in space and time) could either reflect certain complex processes (e.g., growth of a tectonic form) directly, or reflect it through a general tendency, having in fact a more complicated evolution and spectrum; alternatively, they may possess a peculiar significance and not be related to other tectonic structures exposed at the surface. Particularly important for

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the solution of the problem are geological-geomorphological methods which, combined with seismological and other geophysical methods, permit us to determine long-term features and the development of tectonic structure throughout the Earth's crust and the upper mantle more precisely. On the whole, the geological-geomorphological investigations of modern tectogenesis consists in identifying and analysing deformations and many other related peculiarities of the Earth's surface (land forms and Holocene deposits). Air and satellite images are indeed of great help in this.

Requiring no space limitations, geological-geomorphological methods are found to be really advantageous. Unlike instrumentally investigated lines and areas, and unlike ancient tectonic structures preserved in fragments, young deformations can be investigated throughout their entire length and are represented in their real spatial relations. If considered on the geological time scale, all Holocene tectonics formations are coeval; however radiocarbon datings, as well as archeological and historical data, enable us to investigate the Holocene tectonics both on the geological and in the real time scale and to demonstrate the complicated and often uneven course of the processes of evolution.

The idea of the application of geological-geomorphological methods to the investigation of modern movements of the Earth's crust is not new. But we consider it necessary to emphasize its significance once again and in this connection to dwell on certain recent results of studies of crustal disturbances in tectonically active regions and on some new aspects of this problem. We shall discuss three interrelated aspects of the geological-geomorphological study of modern tectonic movements:

1. Holocene tectonic deformations and disturbances of the Earth's crust in vast areas of the Alpine-Asian orogenic belt;
2. Deep-seated components of modern tectonic processes, recorded at the surface;
3. Geological-geomorphological criteria for the assessment of seismically dangerous tectonic movements.

There is sufficient evidence to show that modern deformations of the Earth's crust are, in fact, recorded everywhere. However, it is only within mobile belts and within present-day orogenic regions that high velocities and high gradients of the vertical and horizontal components of tectonic movements lead to the appearance and active development of faults. We have used the latter as a very important and easy way to study characteristic features of modern movements of the Earth's crust for the purpose of evaluating spatial features and the nature of modern tectogenesis in the vast European continent.

A map of active faults in the USSR and adjacent areas was prepared at a scale of 1:8,000,000 (authors: A.I. Kozhurin, N.V. Lukina, V.I. Makarov and V.G. Trifonov of the Geological Institute of the USSR Academy of Sciences; K.G. Levi and S.I. Sherman of the Institute of the Earth's Crust of the Siberian branch of the USSR Academy of Sciences; and S.S. Shults of VSEGEI). The map shows major faults that enable the authors and other researchers to

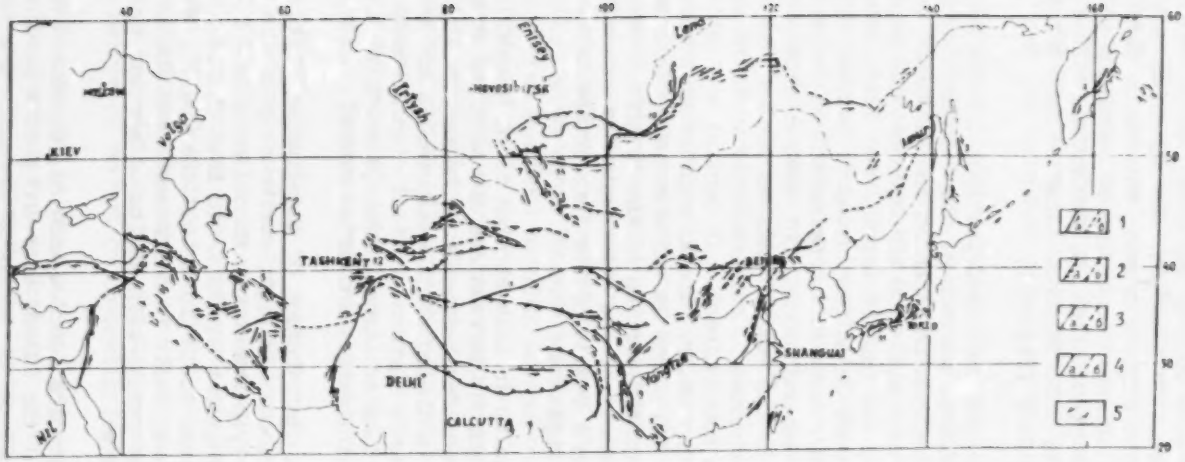
follow traces of Holocene movements. In addition to ground observations, air-borne and satellite photos were used to map such faults, which are grouped according to morphological types. In addition, the map shows modern and Holocene volcanoes, indicates the Earth's crustal thickness, and epicentres of strong earthquakes since 1900, arranged according to magnitude and focal depth. Using this map and data by C. Allen, M. Berberjan, N. Wellman, Ding Guyoyu, N. Pavoni and K. Khuzit, V.G. Trifonov later on made a map of active faults in Asia between 20° and 60°N (figure 1).

Both the above-mentioned maps confirmed previous conclusions and hypotheses about the predominance of horizontal displacements over vertical ones, about the rapprochement between the Arabian and Hindustan peninsulas and the more northern areas of Eurasia and, as a consequence, the separation of mountanous massifs of Anatolia, the Islamic Republic of Iran, Afghanistan, the Tadzhik Depression, Tibet and west China from areas of maximal collision and merging.1/ Besides the Earth's crust, active deformations involve not only boundaries of lithospheric plates and blocks, but also embrace mobile belts, hundreds of kilometres wide. In the Pamir-Himalayas region, for example, the area of intense Holocene disturbances is commensurable with the rather poorly deformed part of the Hindustan subcontinent. In central and eastern Asia, the belt of recent deformations grows wider. The kinematics of numerous diversely directed faults which conforms (and this is quite natural) to late Quaternary and Holocene folded deformations and warping of the Earth's crust, could be more correctly regarded as evidence of the deformation of extensive lithospheric masses, and not as a result of the interaction between a limited number of rigid plates and microplates.

Nowadays, most active faults in Asia stretch along boundaries between ranges and intermontane and piedmont depressions and vertical displacements, of overthrust, upthrow and normal fault-types must be recorded along such marginal faults. In addition to these, strike-slip faults are found along the majority of faults, which commonly surpass vertical displacements of coeval formations, often being many times as large. Average velocities of Holocene strike-slips are measured in millimetres and often exceed 1 cm per year.

Areas with a predominant distribution of longitudinal left and right displacements can be distinguished. So right strike-slip faults dominate in the area extending from North Tyan-Shan up to Mongolian Altai and on the eastern margin of the Asian continent Kamchatka to East China; a left strike-slip fault recorded in the south China belt changes its strike from east-north-east near the Altyntag fault to north-west near the Ksyanshuj and Ksyaochan faults. The trend of strike-slip faults of similar type changes considerably in other belts as well.

Dislocations along longitudinal active margins, expressed mostly in strike-slip faults, are typical for island arcs and active margins of the Pacific, but not without exceptions.2/ Strike-slip faults are found only in areas with a granite metamorphic layer; in structures with oceanic transitional crust, they give way to distrubances of a different kind. Moreover, the location of hypocentres and the focal mechanisms of earthquakes show that the right-lateral median line of Japan goes no deeper than 15-20 km;



Faults in Asia between 20° and 60° N, active in the Holocene. Prepared by V. G. Trifonov on the basis of published data by C. Allen, M. Berberjan, N. Wellman, Ding Guoyu, A. Kozhurin, G. Levi, N. Lukina, V. Makarov, A. Nikonov, N. Pavoni, K. Khusit, S. Sherman, S. Shults and personal observations. Active faults are shown on the map by figures. 1) Altyntag, 2) East Sakhalin, 3) Eastern face of the Central Kamchatka depression, 4) Main Himalayan boundary, 5) Shansi graben, 6) Darvaz-Alay, 7) Dzhungar, 8) Kobdin, 9) Ksyanshuy, 10) Ksyaochan, 11) Primorsky of Baikal, 12) North Tyan Shan, 13) Median line of Japan, 14) Talas-Fergana, 15) Khangay.

Figure 1

lower, at a depth of about 30 km, a structure of a different direction and of another kinematic type was found in the same region. Strike-slip faults obviously dominate in the upper part of the continental crust. Here they play a much more significant role than was previously considered to be the case.

As compared with the areas with strike-slip faults, those areas with dominating fold-overthrust Holocene disturbances (like the outer zone of the Pamirs and Himalayas) or active strike-slips -- separating faults (like the Baikal depression or Shansi graben), are rather small, indicating a limited structure-forming power of rapprochement and separation of uppermost crustal sheets. These sheets, being disrupted by numerous faults, may not convey structure-forming powers to large distances, and strike-slip faults do not seem to be a result of such interactions; rather they reflect movements of deeper lithospheric masses. The latter suggests that deformation properties, tectonic styles and movement velocities are different at different lithospheric levels, i.e., here we are dealing with tectonic layering and this should necessarily be kept in mind if one is dealing with modern movements of the Earth's crust and particularly with structural interpretations of instrumental observation data and the preparation of corresponding forecasts.

It is generally known that in many cases an instrumentally established picture of movements of the Earth's crust corresponds better to the structure of geophysical fields which characterize deep-seated layers of the lithosphere than to the near-surface geological structure. A similar tendency has long been familiar to geomorphologists, who also investigate space-time relationships and other aspects of the development of crustal landforms.

Some time ago, in analysing the nature of lineaments recorded in satellite pictures of the Earth's surface, but without marked structural, lithological or other geological features being observed, we came to the conclusion that many such lineaments reflect active (including seismoactive) elements of the structure of the deep layers of the Earth's crust and upper mantle.5/ Subsequent investigations carried out by us and by other authors gave sufficient evidence in favour of this conclusion and allowed us to define various geological, structural-tectonic, geomorphological, landscape and other features of the Earth's surface which, if taken together, make up such lineaments and other similar formations, which we generally regard as concealed deep structures.4/ 5/

On the whole, it is obvious that here we have rather widely spread manifestations on the Earth's surface of deformations and other processes which take place in deep layers of the lithsphere and whose type, nature, morphology and trend are not repeated in near-surface formations. This phenomenon requires particular attention. On the Earth's surface, such deformations are characterized by considerable width and small gradients of change of various characteristics. This refers particularly to young Holocene forms which are of special interest to us at present. The fact is that during so short a period of time as the Holocene, the deposits have not accumulated considerable changes in composition, thickness, position or other features. That is why these changes are often missed during land observations and are not kept in mind during interpretations which are usually done on the basis of the near-surface structure. Particular attention should be paid to active forms of such kinds which do not conform to the near-surface structure.

A comparative analysis of the activity and ways of expression of active structures in different lithospheric layers that we made, using geophysical and seismic data for many areas of the Alpine-Asian mobile belt, has made evident the structural-dynamic and kinematic variety of the lithosphere.6/ There is every reason to suggest that the morphology, kinematics, direction and velocity of modern deformations are different at various lithospheric levels. This leads to the appearance of compensatory decollements and other transformations along some more or less extended subhorizontal zones, i.e., to tectonic layering of the lithosphere (figure 2). This latter can easily be augmented by spacial distributions of seismic phenomena in a section of the lithosphere and by corresponding changes of their characteristics or the characteristics of the environment in which an earthquake begins.6/

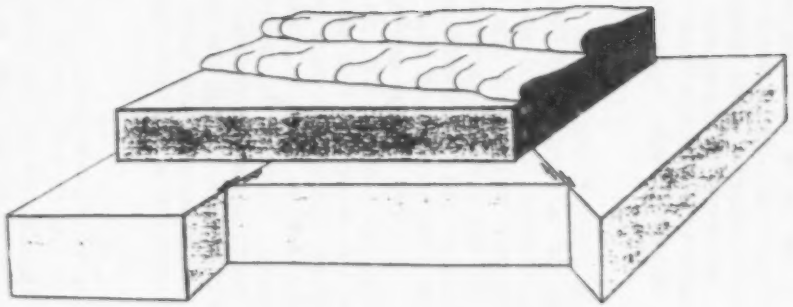
Modern deformations of the Earth's surface reflect the processes going on deep in the lithosphere. Thus, in studying modern movements of the Earth's crust it is necessary to take into account and to investigate these processes in order to interpret the data obtained from instrumental observations correctly. In this respect, the most effective methods of analysis of deep-seated tectonics are: correlation of structural-geomorphological and geophysical data, space-time analysis of earthquake focal distributions and of their mechanisms and peculiarities, study of heat and geochemical anomalies, and analysis of air-borne satellite data.

The aspects of the geological-geomorphological study of modern movements of the Earth's crust mentioned are extremely important for working out criteria for identifying places of strongest earthquakes. This work includes the following geological and geomorphological investigations:

1. Study of neotectonic structures as a whole and the tendencies of their evolution and reconstructions, with a view to identiying areas of the highest Late-Quaternary and modern activity;
2. Mapping of areas of possible Late-Quaternary activity of systems of active tectonic disturbances and deformations of the Earth's surface that appeared and were rejuvenated in the Holocene;
3. Within active systems and zones, the definition of areas of possible strong earthquakes by discovering traces of past earthquakes and places of possible concentrations of tectonic strain in vast mountain masses.

The last point needs some explanation. Tectonic movements in active zones may find their expression either in strong impulses, or in creep and relatively weak impulses. High tectonic activity is an indispensable condition for strong earthquakes, but alone it is not sufficient. There should exist, in addition, conditions for quite long concentrations of strain in an extensive volume of rocks. Such a possibility may be defined in two ways.

The first one is based on the study of paleo-seismodislocations -- traces of disturbances of the Earth's surface, occurring due to previous strong earthquakes, prehistoric and Holocene ones included.



Scheme of variably deformed area

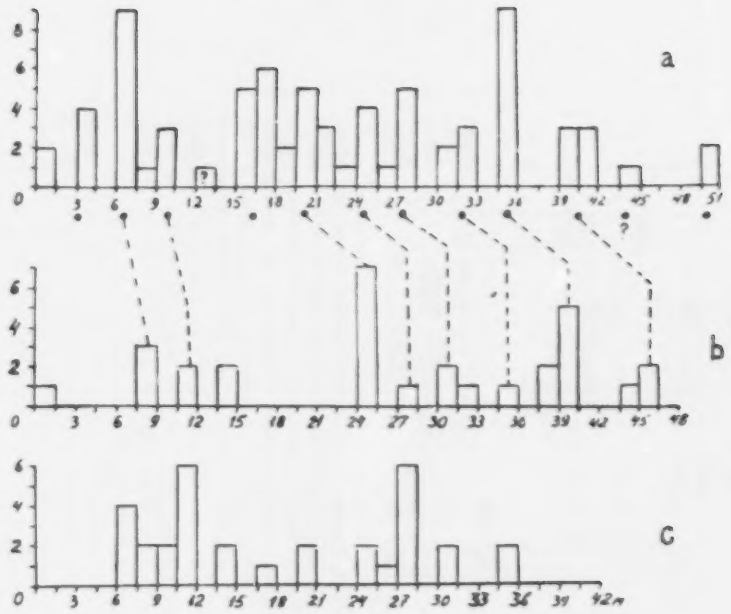
Figure 2

This method enables us to determine the average recurrence period of strong earthquakes in any section of the active zone; the latter cannot be done with instrumental observations because they are short-term. Besides, it is also possible to predict the force of possible seismic impacts, due to the fact that different types and complexes of seismodislocations take place under different tremor intensities. The works by V.P. Solonenko and other seismotectonists of the Irkutsk school who have been involved in investigations of various areas of South Siberia, as well as the works by V.K. Kuchay and A.A. Nikonov, who mainly used data from Central Asia have considerably advanced the study of paleo-seismodislocations of seismo-gravitational type. To identify traces of seismic impulses in strike-slip faults along most active faults is found to be very difficult. One of the authors of this article has elaborated a method of such analysis of active faults.1/ 7/ 8/ It is based on material from Mongolia, central Asia and the best of the United States. Numerous measurements of strike-slips of non-coeval landforms and deposits were made and the ages of sediments accumulated in the process of such movements were determined for this purpose (figures 3, 4).

However, this method has space limitations due to insufficient conservability or due to the absence of seismodislocations. For this reason, we have to use indirect methods to discover zones and areas of high concentrations of tectonic strain in vast volumes of the Earth's crust. Among these methods are: the definition of the morphological and kinematic characteristics of Holocene disturbances and the clarification of the conditions of origin and most possible mechanisms of the foci of strong earthquakes. No less important is the study of the geological structure of active zones (their structure, substance, composition, degree and nature of dislocation, and other properties which determine the strength of rock masses). And finally, a very important element of such an analysis is the study of the deep-seated tectonics of active zones and identifying areas of possible tectonic strain concentration. Discovering active structures concealed at a certain depth is of particular importance; their morphology, orientation and other parameters are different from the structures of the near-surface layer, in such a way, the nature of the 1976 and 1984 Gazliy catastrophic earthquakes in central Kyzyl Kum was investigated (figures 5, 6).9/ 10/

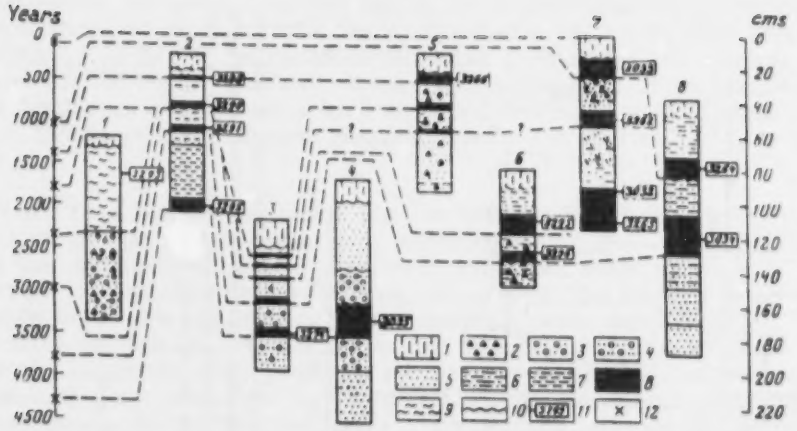
Thus, the application of geological-geomorphological methods for the study of modern tectonic movements of the Earth's crust is necessary to obtain a more complete picture of their activity and of their relation with tectonic structures, and for a more correct practical application. In view of this, the careful study of Holocene tectonics as a whole is necessary as well as Holocene deformations and the régime of their develoment. It would seem useful to start the preparation of a map showing the active faults of the World which could present a complete picture of modern movements of the Earth's crust.

In studying, and particularly in interpreting, modern movements of the Earth's crust, one should keep in mind tectonic layering of lithosphere, and the specific forms by which the deformations reflecting the evolution of deep-seated processes are represented on the Earth's surface. No less



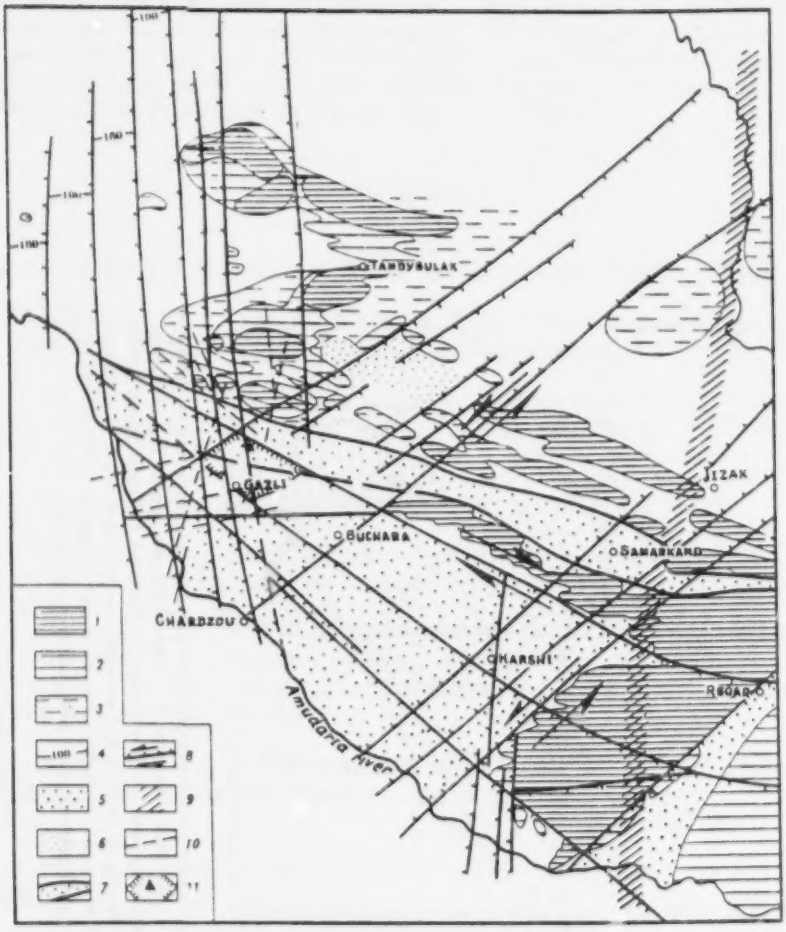
Histogram of the distribution of amplitudes of Holocene right strike-slip faults, of water flows and other minor landforms along the Talas-Fergana fault (Tyan Shan): a) from Kokkia pass to upper reaches of the Pychan river (thick points — possible traces of strong earthquakes); b) from the upper reaches of the Pychan river to Kylkow valley; c) in the Kurovea and Keklikbel river basins.

Figure 3



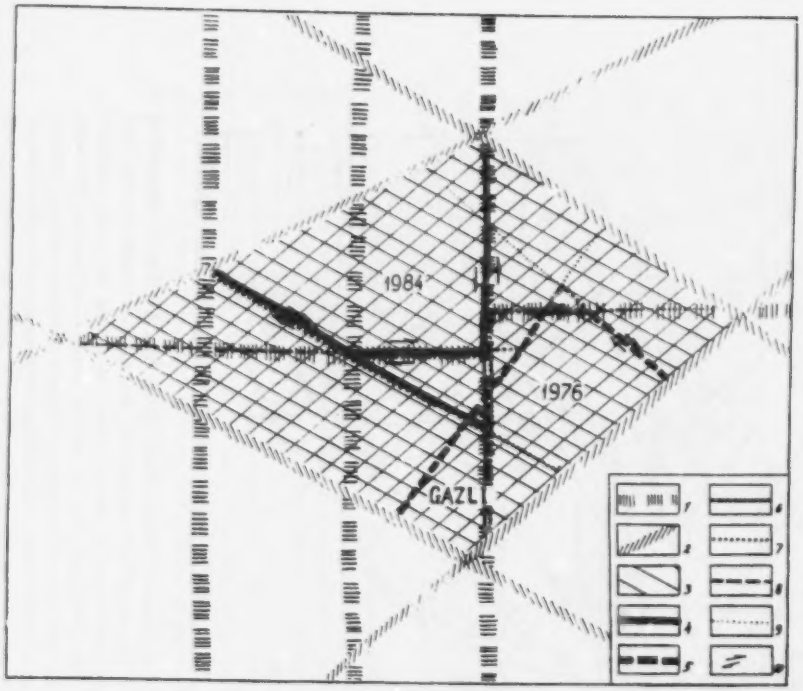
Comparison of sections of Holocene deposits of small impounding lakes and enclosed depressions of the Khangay fault zone (North Mongolia): 1) soil layer; 2) pebbles; 3) gravels; 4) course-grained sand; 5) middle and fine-grained sand; 6) sandy loam; 7) loam and clay; 8) loam and clay, rarer – sandy loam, enriched in organic matter; 9) peat bog; 10) erosion surface; 11) radiocarbon datings of the age of deposits, by L. D. Sulerzhitsky in the Geological Institute of the USSR Academy of Sciences in 1982. (3032 = 2690 ± 110 years; 3033 = 1090 ± 50 years; 3034 = 3720 ± 160 years; 3035 = 4280 ± 250 years) and 1983 (3262 = 1300 ± 80 years; 3264 = 920 ± 60 years; 3265 = 2900 ± 90 years; 3266 = 1300 ± 250 years; 3274 = 4210 ± 80 years; 3288 = 1400 ± 100 years; 3290 = 1780 ± 200 years; 3291 = 3870 ± 180 years; 3293 = 2360 ± 100 years; 3295 = 4340 ± 20 years; 3298 = 3280 ± 180 years; 3297 = 2950 ± 150 years); 12) proposed sites of catastrophic earthquakes in the time scale.

Figure 4



Scheme of present-day arrangement of deep-seated structures in Central Kyzyl-Kum (according to Makarov *et. al.*, 1984): 1–3) anticline uplifts (basement folds), their zones and systems (Central Kyzyl Kum uplifts are distinguished according to the degree of relative upwarming of the fold basement); 4) position of 100 m contour line of the Earth's surface in the area between Amu Darya and Syr Darya; 5) zones of most active downwarping and of accumulation of Neogene-Quaternary deposits; 6) deepest depressions within Kuldzhuktau-Nuratau system of uplifts; 7) general contouring of the Zeravshan synclinal zone; 8) zones of flexure faults of concealed type (striations are directed to the lowered limbs, pointers indicate the direction of possible dislocations along these zones); 9) Turkestan-Akchay lineament (zone of concealed deep disturbances of the Earth's crust); 10) faults proposed on the basis of the results of analysis of satellite pictures; 11) contour of seismoactive block and seismostation Karakyr.

Figure 5



Scheme of active lineaments and of principal seismic dislocations of the region of the 1976 and 1984 Gazliy earthquakes. 1–2) major lineaments of orthogonal (1) and diagonal (2) orientations; 3) Earth's crust block marked by major seismic dislocations of 1974–1984; 4–5) mean lines of possible seismic dislocations of 1984 (4) and 1976 (5); 6–7) additional lines of possible seismic dislocations of 1984 (6) and 1976 (7); 8–9) directions of possible occurrence of weak dislocations of 1984 (8) and 1976 (9); 10) proposed directons of possible strike-slip faults according to geological evidence.

Figure 6

important is the application of data on modern movements of the Earth's crust for studies of its deep-seated structure. This aspect of the investigations evidently needs to be further elaborated. For a better understanding of modern geodynamics and the processes taking place in deep lithospheric horizons, extensive work is needed on measuring modern deformations of the lithosphere along elongated transregional profiles.

NOTES

1/ Trifonov, V.G., Late Quaternary Tectonics, Nauka, Moscow, 1983.

2/ Kozhurin, A.I. and Trifonov, V.G.,. "Young Strike-Slip Faults of the Pacific Margin", Geotectonics, vol. 16, No. 2, (1983) pp. 93-104.

3/ Makarov, V.I., Trifonov, V.G. and Shchukin, Yu. K., "Images of Fold Belts Deep Structure on Satellite Pictures", Geotectonics, 3, (1974), pp. 114-132.

4/ Space Information for Geology, (Nauka, Moscow, 1983).

5/ Makarov, V.I., "Active Deep-Seated Deformations and Lithosphere Seismicity of Neotectonic Active Belts". Major Seismotectonic Problems. (Nauka, Moscow, 1986), pp. 36-39.

6/ Makarov, V.I., Trifonov, V.G. Shchukin, Yu. K., Kuchay, V.K. and Kulagin, V.K. Tectonic Layering of the Lithosphere of Neotectonic Active Belts. (Nauka, Moscow, 1982).

7/ Trifonov. V.G., "Active faults and Seismicity", In Present-day Tectonic Activity of the Territory of the USSR, (Nauka, Moscow, 1984), pp. 24-34.

8/ Trifonov, V.G., "Peculiarities of the Development of Active Faults", Geotectonics, 2, (1985), pp. 16-26.

9/ Makarov, V.I. and Shchukin, Yu. K., "Assessment of the Activity of Concealed Faults", Geotectonics, vol. 13, No. 1, (1980), pp. 65-73.

10/ Makarov, V.I., Lukina, N.V. and Shchukin, Yu. K., "Investigation of Residual Deformations of the Earth's Surface in an Epicentral Zone. Geologo-Tectonic Characteristics of the Central Kyzylkum: Gazliy Earthquakes", Geologo-Geophysical Nature of Foci., (Nauka, Moscow, 1984), pp. 106-130.

REMOTE SENSING OF PHYSICAL AND BIOLOGICAL PROPERTIES OF COASTAL WATERS, ESTUARIES AND WETLANDS

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ABSTRACT

Remote sensors on satellites and aircraft combined with ship measurements can provide synoptic observations of coastal and estuarine phenomena which vary rapidly in time and space. Coastal applications of remote sensing require a wide assortment of sensors, including aerial film cameras for beach erosion and vegetation mapping; multispectral scanners for wetlands biomass and estuarine water property studies; thermal infra-red scanners for mapping surface water temperatures and currents; microwave devices for salinity or wave measurements; and underwater cameras and acoustic systems for benthic observations. Meaningful observation of physical and biological processes in estuaries (e.g., turbidity maximum dynamics or phytoplankton bloom development) requires the close co-ordination of satellite/aircraft and ship/field data acquisition.

Recent progress in optical modelling and instrument design is making estuarine remote sensing quite effective. Multispectral solid state video cameras and other sensors are being developed which can be flown on inexpensive, small aircraft. Deployed in conjunction with satellites, these airborne sensors can observe tidal, seasonal, annual variations and spatial distributions of phytoplankton blooms, sediment plumes, estuarine fronts and circulation patterns. New hydrologic and optical databases are being used to refine and invert practical models, such as the singly-scattered irradiance model, to detect chlorophyll, suspended sediment and dissolved organics in turbid estuaries. Inexpensive microcomputers and user-friendly software facilitate the analysis of Landsat Multispectral Scanner (MSS), Thematic Mapper (TM), SPOT, NOAA/AVHRR, Nimbus/Coastal Zone Color Scanner (CZCS) and other satellite data at small, local laboratories and research centres. These new techniques enable scientists to monitor the environmental quality of coastal waters and compare the susceptibility to degradation (e.g., eutrophication) of estuaries that various national and international programmes require.

This paper, which was presented at the United Nations/Food and Agricultural Organization/European Space Agency Meeting of Experts on Remote Sensing and Satellite Meteorology Applications to Marine Resources and Coastal Management organized for Member States on the Atlantic Coast of Africa, Maspalomas, Canary Islands, Spain, 8-12 May 1989, does not necessarily reflect the view of the United Nations.

INTRODUCTION

The inherent values of tidal wetlands and estuaries in terms of carbon fixation, fisheries habitat, nutrient assimilation, global elemental cycling, water storage and sediment stabilization have been established.1/ These natural contributions of wetlands to coastal ecosystems, as well as the less tangible values related to aesthetics, education, and recreation for mankind,2/ suggest that coastal wetlands are extremely important systems for the maintenance of the quality of coastal environments. Even though estuarine ecosystems are among the most productive ecosystems on Earth, relatively little information is available on the seasonal and annual variability of the growth and net primary productivity of tidal marshes and estuaries. Ecosystem level study is difficult in estuaries primarily because of the size of the system. Input data for ecosystem studies are normally extrapolations from relatively small samples taken at representative points within the system. The advent of the Landsat and NOAA satellites series has provided data-gathering systems capable of collecting data for entire ecosystems.

Compared to the open ocean, wetlands and estuaries are very small and undergo rapid changes due to tidal effects. Therefore, observation requirements for coastal features differ significantly from requirements for open ocean investigations. Spatial and temporal resolution requirements become more severe as one moves closer to the coast. This is illustrated in table 1, which compares spatial and temporal resolution requirements for various coastal and open ocean applications. For instance, Gulf Stream meanders and warm core rings beyond the shelf can be sufficiently mapped twice weekly with 1 kilometre resolution; fronts and ocean-dumped waste plumes on the continental shelf can be tracked about every four hours with 50 metre resolution; while observation of tidal-induced estuarine fronts requires one-half hourly observations at about 10 metre resolution.

MAPPING COASTAL VEGETATION AND LAND USE

An awareness that wetlands might possess value in their natural unaltered state began in the 1930s, but did not surface as a national policy until the late 1960s. The first major manifestation of national concern for natural systems was the passage of the National Environmental Policy Act of 1969.3/ This action was reinforced in 1972 with the passage of the Coastal Zone Management Act that focused directly on the coast and its wetlands. Coastal states, in some cases, had already enacted legislation or followed the federal lead by enacting legislation protecting and/or regulating activities within wetlands.4/ The inherent values of wetlands to society for natural waste treatment and aesthetically-pleasing environments 2/ were rapidly becoming apparent.

The result of these events has been close scrutiny of changes in wetlands acreage over time. The primary means of monitoring changes in aerial extent of marshes has been through aerial photographic surveys and, recently, through more advanced remote sensing techniques.5/ Due to the fact that

Table 1. RESOLUTION REQUIREMENTS FOR REMOTE SENSING

	TEMPORAL	SPATIAL	SPECTRAL	RADIOMETRIC
OCEAN	3 DAYS	1 KM	MEDIUM	HIGH
SHELF/COAST	1/2 DAY	100 M	MEDIUM	HIGH
ESTUARIES	1 HOUR	20 M	HIGH	HIGH
WETLANDS	3 YEARS (1 MONTH)	30 M (10 M)	MEDIUM (HIGH)	MEDIUM
LAND USE	3 YEARS	30 M (10 M)	LOW	LOW
AGRICULTURE	1 YEAR (2 WEEKS)	30 M	LOW (HIGH)	LOW
GEOLOGY	6 MONTHS (1/2 DAY)	100 M (10 M)	LOW (HIGH)	LOW

remote sensing techniques provide for low cost per acre and speedy analysis, it is useful for monitoring the effects of man's activities upon marshes. A major application of remote sensing activities has been to monitor the delineation and computation of marsh acreage lost. This, in itself, represents only a part of the impact of man's activities upon marshes.

Remote sensing as a tool for evaluation of vegetative communities began with the aerial camera. With advances in the knowledge of the physics of remote reconnaissance 6/ and with advances in sensor technology, remote sensing instrumentation developed as a means to probe areas of the electromagnetic spectrum invisible to panchromatic and infra-red files.7/ While new areas of remote sensing developed, the usefulness of film media for investigating ecological conditions in natural 8/ and agricultural 9/ vegetation was being realized. Early reports using aerial photography for seaweed surveys in Nova Scotia 10/ and forest vegetation surveys near Quebec 11/ demonstrated the utility of this remote sensing technique.

Inventories of wetlands using primarily colour infra-red aerial photography began in the late 1960s as legislation protecting coastal wetlands was being formulated. Stroud and Cooper 12/ used colour infra-red photography and appropriate ground calibration to estimate the net primary productivity in North Carolina salt marshes. A similar study by Reimold et al. 13/ in Georgia salt marshes reaffirmed the association between colour tones on colour infra-red photography and different quantities of Spartina alterniflora net primary productivity. Microdensitometry and multispectral photographs were used to delineate vegetation types in California 14/, South Carolina 15/, New Jersey 16/ 17/, Delaware 18/, Wisconsin 19/, and Vermont 20/. These efforts at quantification of pigment density from photographs or transparencies and the combination of multiband photography for species discrimination were generally successful.

Additional results dealing primarily with mapping, wetland inventories and comparisons of remote sensing media for accomplishing the inventories included 21/ for Maryland wetlands, Gallagher et al. 22/ 5/, Gallagher and Reimold 24/, and Gallagher 25/ for Georgia salt marshes, Anderson and Wobber 17/ for New Jersey wetlands, and Benton et al. 26/ for coastal Texas marshes. Aerial photography was also useful for delineation and discrimination of types of freshwater marshes. Successful inventories using aerial photography in freshwater marshes included studies of the Florida Everglades 27/ 28/, Nevada marshlands 29/, Lake Erie fringe marshes 30/, wetlands in glaciated regions of Minnesota 31/, freshwater tidal wetlands of Maryland 32/, forested and nonforested wetlands of Tennessee 33/, and non-tidal inland wetlands in Florida 34/. Seasonal aerial photographs contained the necessary information for determination of evergreen/deciduous boundaries and separation of deciduous canopy classes in the Great Dismal Swamp.35/

With the launching of the Landsat series of satellites in the early 1970s, MSS data became available. The coarse resolution of the data (57m x 79m pixels) limited surveys using MSS data to relatively large tracts of wetlands, and the MSS data were usually supplemented with high resolution aerial photography. Mapping and classification of marshlands using MSS data were accomplished in coastal South Carolina and Georgia marshes 36/, in

Virginia coastal marshes 37/, in Delaware coastal marshes 38/, in Louisiana marshes 39/, in lacustrine, palustrine and riverine wetlands of Michigan 40/, in the Columbia River wetlands of Oregon 41/, and in prairie wetlands of North Dakota 42/. The combination of MSS data and aerial photography was also used to develop vegetation maps for forested wetlands like the Great Dismal Swampt.43/ 44/.

Thompson et al. 45/ discuss many of the operational and photogrammetric considerations necessary to convert remote sensing data in wetlands to reliable vegetation maps. Additional mapping considerations and problems unique to coastal mapping are enumerated by McEwen et al. 46/ and Masry and MacRitchie 47/. The massive effort to inventory and to classify wetlands in a useful format for wetlands management personnel, however, had problems. Penney and Gordon 48/ provide an interesting discussion of inventory and management problems from the manager's point of view.

The advent of digital spectral data in specific spectral wavebands from the Landsat MSS sparked a new era in remote sensing. Data no longer had to be extracted from photographs. Instead, data already available in digital form allowed direct, quantitative treatment of the radiance data. Ground-gathered spectral reflectance data had been collected for many agricultural crops.49/ 50/, 51/, 52/ Similar data were also necessary for interpreting spectral signatures from wetland plants. Carter and Anderson 53/ and Pfeiffer et al. 54/ provided in situ spectral reflectance data for a number of wetland plant species. The spectral radiometric data constituted a basis for interpretation of satellite imagery, and also provided useful data for evaluating vegetative canopies from the ground.

Bartlett and Klemas 55/, compare the cost of mapping coastal vegetation using ground surveys, aircraft and satellites. They suggest that for simple vegetation inventories of small test sites, aerial photography should be seriously considered. However, for repetitive observatons of vegetative changes, biomass and water properties of areas larger than 10,000 hectares, use of Landsat MSS or thematic mapper (TM) data may provide considerable cost savings and speed up the work considerably. The spectral bands and 30-metre resolution seem particularly well-suited for mapping narrow coastal features, such as tidal marshes and submerged aquatic vegetation beds.56/

ASSESSMENT OF WETLANDS BIOMASS AND PRODUCTIVITY

Ground-based spectral data were found to have a high correlation with the leaf area index of a tropical forest.75/ Marshall 58/ attempted optical density measurements in S. alterniflora salt marshes as a rapid means of biomass comparison. However, his limited data were inconclusive. By the mid-1970s, ground-gathered spectral radiance data in the region and in the near infra-red region were successfully related to above-ground biomass of a variety of vegetation types. The first group to report success in relating spectral data to gramineous biomass was Tucker et al. 59/ and Pearson et al. 60/. They presented data indicating a very strong relationship between biomass of blue grama grass and spectral radiance ratios. Similar research in wetlands showed much of the same results for gramineous wetlands species

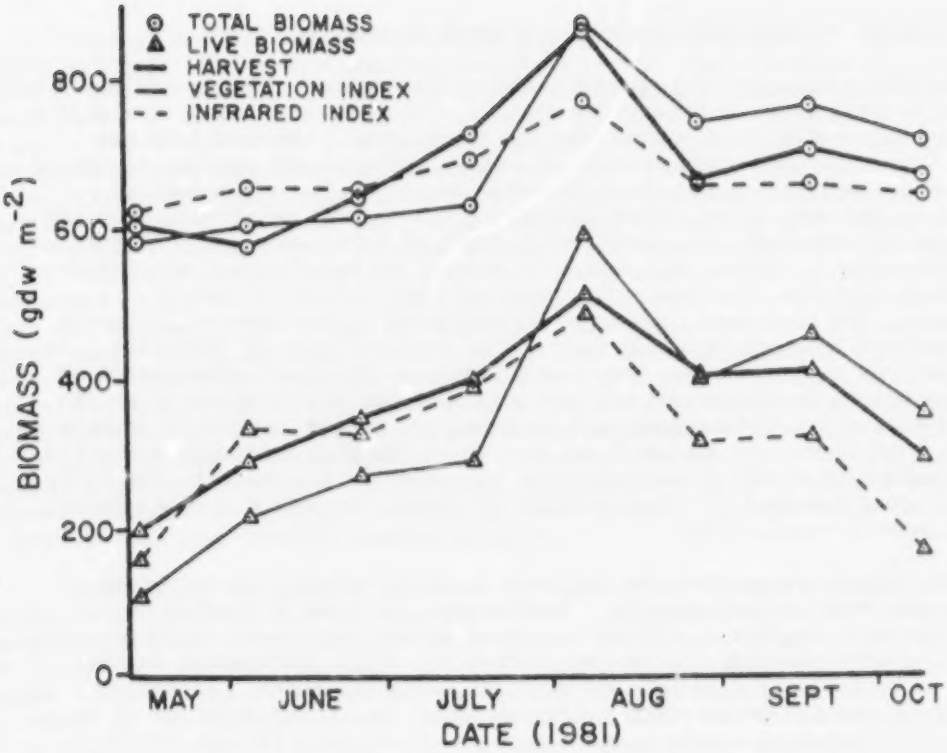
61, but some difficulty accrued when working with the broadleaf shrub, Iva frutescens 62/.

Subsequent work with the hand-held radiometers in Delaware wetlands 63/ 55/ 64/ 65/, in marshes typical of the Danish Wadden-Sea area in Denmark 66/, and in English bogs and marshes 67/ 68 confirmed the correlation of spectral radiance data with selected canopy characteristics of wetland plant communities. One of the most important canopy parameters consistently related to spectral data was biomass. Other studies concerned primarily with species discrimination using hand-held radiometers included Best et al. 69/ for hydrophytes occupying the glaciated wetlands of the Prairie Pothole region of South Dakota, Ernst Dottavio et al. 70/ for freshwater wetlands in northeastern Indiana, and Budd and Milton 71/ for a variety of salt marsh plants common to Southern England marshes.

Early work by Bartlett 61/ 63/ determined that green biomass, a percentage of live biomass, total biomass, and canopy height had significant correlation with spectral reflectance of S. alterniflora and salt hay (Distichlis spicata/Spartina patens mixture) communities found in Delaware salt marshes. Bartlett obtained these results using a radiometer configured to the four spectral bands found on the Landsat MSS. The most useful spectral waveband combination was the red band (600-700nm) and a near infra-red band (800-1100nm).

A database of spectral and biomass information was compiled for the dominant salt marsh plant S. alterniflora by Hardisky et al. 72/, who monitored short and tall swards of S. alterniflora over entire growing seasons. Spectral data were collected with a hand-held GSFC Mark-II radiometer. The radiometer was configured with three spectral bands corresponding to bands 3, 4 and 5, respectively, of the thematic mapper. A red band (630-690nm) sensitive to chlorophyll density, a near infra-red band (760-900nm) sensitive to tissue structure or biomass, and a middle infra-red band (1550-1750nm) sensitive to leaf moisture were used. Spectral radiance data were collected over designated plots and the biomass of each plot was determined by harvesting. Biomass and spectral data were regressed over the growing season, yielding models that included seasonal canopy changes and seasonal variations in solar irradiance. The models were suitable for biomass predictions throughout the growing season (figure 1) with the spectral data having high correlation with live S. alterniflora biomass throughout the growing season. In the model, the spectral radiance data are expressed in terms of the Infra-red Index, which is defined as the difference of TM bands 4 and 5 divided by their sum. Biomass measurements conducted with TM and SPOT data had accuracies of about 10 per cent.73/

Supporting studies included an assessment of negative biomas response for S. alterniflora to increases in soil salinity 74/ and an assessment of positive biomass response for S. alterniflora to irrigations of sewage effluent (nitrogen addition) and freshwater (soil salinity dilution). Changes in canopy moisture in response to changes in soil salinity correlated negatively to changes in spectral radiance indices, and enhanced biomass production resulting from freshwater or sewage effluent irrigations correlated positively with increases in measured spectral radiance indices.75/ An



Remote sensing and harvest estimates of biomass over the growing season.

FIGURE 1

additional study determined that canopy changes resulting from amending an S. alterniflora marsh with heavy metals (copper and zinc) could be detected spectrally.76/ Live and dead biomass amounts showed to be significantly higher in copper amended areas than in control areas. This difference in canopy biomass components (proportion of live and dead biomass) was successfully detected with spectral data. From these studies, spectral discrimination of small biomass changes (on the order of 40 gdw m^2) was shown to be feasible and the database for future biomass estimation using spectral data was established.

REMOTE SENSING OF ESTUARINE CURRENTS AND WATER PROPERTIES

Passive remote sensing systems sense either reflected solar radiation or radiated thermal infra-red/microwave energy. The solar radiation wavelengths attenuate exponentially by water; whereas the thermal infra-red ones are limited to a very thin surface layer of water. Only in the surface layers of the water column, the signal-to-noise ratio decreases in an exponential manner. In the open ocean, where scattering and absorption effects have the same order of magnitude, the penetration depth of detectable visible light may exceed 50 metres. Coastal and estuarine waters are more turbid and contain complicated mixtures of dissolved organic and particulate inorganic substances. The increased scattering by suspended matter results in Secchi depths of less than one metre in many of the world's bays and estuaries. As one moves from the open ocean into coastal waters, the light attenuation in the water column increases and the wavelength of optimum penetration shifts from the blue-green to the green and, eventually, to the red due to increasing absorption of blue light by humic acids. While the high turbidity makes the discrimination of specific substances in the water more difficult, turbidity patterns reflect more light than Landsat MSS bands can detect despite their low radiometric sensitivity.

The dynamic range of water radiance is about an order of magnitude smaller than that of land targets. Furthermore, in coastal studies one frequently needs to distinguish water masses having only small differences in particulate or dissolved content and, therefore, small differences in the spectra of backscattered light. As a result, more radiometric sensitivity is required for coastal water studies than those of land. One solution is to increase the number of quantization levels, such as going from 64 on MSS to 256 on TM, AVHRR and CZCS. Another approach is to decrease the dynamic range of the sensors and to match them more closely to the reflectance extremes of the known water types around the globe. The dynamic ranges of MSS, AVHRR and CZCS are compared in table 2. Obviously, AVHRR and CZCS are designed to be more sensitive to small radiance variations from different water types than Landsat MSS.

Using digital enhancement techniques, Landsat MSS, NOAA/AVHRR and Nimbus/CZCS have been used effectively to study sediment patterns, estuarine circulation, frontal dynamics, and ocean-dumped waste dispersion (Klemas, 1980, Klemas and Philpot, 1981). The suspended sediments and wastes frequently act as natural tracers, enabling even Landsat MSS to detect the patterns. To improve the contrast of water features, contrast stretching is

frequently applied to satellite imagery (Maul and Gordon, 1975). Good examples of multi-level observations of estuarine circulation properties are offered by Klemas et al. 77/ in Delaware Bay, and by Gagliardini et al. 78 and Karszenbaum et al. 79 in the La Plate River estuary. Aircraft and ground-based radar techniques are being developed for measuring currents.80/ Of particular interest to estuarine studies is the CODAR system, a mobile coastal radar unit which can map variable surface currents in real time to 70 kilometres using water wave scatter.81/ Currents can also be measured using dyes and drogues tracked from shore or from aircraft.82/ 83/ There are also photogrammetric methods for surveying tidal currents.84/

Coastal erosion and coastal geomorphology have been studied successfully using aircraft film cameras and Landsat.85/ 86/ 87/ The advantage of aircraft photography is that it provides the high resolution required for accurate measurement of beach erosion and accretion. Landsat MSS, however, can provide a geological overview of an entire coastline, including underwater features. Bathymetric maps have been successfully prepared by extracting water attenuation and bottom reflectance from digitally processed Landsat MSS data.88/ 89/ 90/ The water depth algorithm used calculates water depth from Landsat MSS 4 (green light) and MSS 5 (red light) data values for Landsat pixels that are judged by a threshold test to be water. The threshold test is performed on MSS 7 (near infra-red). Pixels whose MSS 7 data values are less than the threshold are judged to be water. The bathymetry software calculates depth values using two algorithms, one for deep water and another for shallow water. In deep water, signals from MSS 4 only are used. In shallow water, signals from MSS 4 and 5 can be used in a ratio algorithm to calculate depth, minimizing the effects of changing bottom reflectances. Following depth processing, depths are aggregated into intervals (generally two metres) and assigned arbitrary colours for filming. Typically, 7 to 10 intervals are filmed depending on the maximum depth of penetration. Landsat TM bands 1 and 2 have further improved bathymetric results.

Water depth can also be measured by the time difference between laser pulses from the water surface and the bottom. Such laser profiles use green wavelengths which penetrate reasonably clear waters 91/. A major limitation of laser depth profiling systems is their inability to penetrate turbid water. Most of the laser systems in use perform satisfactorily when the products (a x h) of the beam attenuation coefficient (a) and the depth (h) are from 6 to 10. Due to the fact that the total attenuation coefficient (a) of the optical beam in the ocean and coastal waters varies from 0.5 to 5.0, attainable depths should range from 20 to 2 metres depending on the turbidity of the water. The Airborne Oceanographic Lidar (AOL) system has shown that a single instrument package can be developed for a wide range of applications and turbidity conditions.92/ Visible images from aircraft or satellites can help provide relative depth profiles which may then be calibrated with airborne laser profilers. Even though powerful laser pulses penetrate the water column to several Secchi depths, a major limitation is their inability to reach bottom in turbid coastal waters. For instance, the turbidities of Chesapeake and Delaware Bays are such that less than half the total area could be mapped with the most powerful laser profiler available.

Table 2. COMPARISON OF SENSOR CHARACTERISTICS

	AVHRR	MSS	TM	SPOT	CZCS[1]
resolution (km)	1.1	.08	.03	.02	.82
frequency (days)	0.5-1	16	16	26[2]	3-5
scene width (km)	2000	180	180	60	1500
# of bands					
reflected	2	4	4	3	5
thermal	3	0	2	0	1
radiometric resolution per count					
red band	.052	.131	.081	.040	.005
near-IR band	.034	.115	.084	.055	.093
($mW\text{-}cm^{-2}\mu m^{-1}sr^{-1}$)					
saturation radiance					
red band	50.	17.9	20.4	10.2	2.9
near-IR band	33.	14.8	20.6	14.0	23.9
($mW\text{-}cm^{-2}\mu m^{-1}sr^{-1}$)					

[1]The CZCS was turned off in 1986 with no plans for a replacement.

[2]The SPOT sensor can be pointed upon request, therefore, an area can be imaged several times during a cycle.

Due to the fact that wave lengths do not penetrate to the bottom of turbid estuaries, to map bottom features reliably, one frequently must turn to underwater television cameras, film cameras or sonar systems operated from boats. Television and film cameras have been used successfully to study ripple formation, current-induced sediment movement, submerged aquatic vegetation and other features, including wrecked ships.93/ Echo sounders and side scan sonar have been deployed to study bottom geological features, search for lost equipment, and track schools of fish and ocean-dumped waste penetration of the thermocline.94/ 95/

Suspended sediment concentrations are of interest to marine geologists and biologists because sediment relates to coastal erosion/siltation, and affects sunlight penetration and marine productivity. With appropriate ground data, suspended sediment concentrations have been mapped from aircraft and satellites.96/ 97/ 98/ 99/ 83/ One of the major problems in calculating suspended sediment concentration from a measured flux is the difference in absorption and scattering of light in the atmosphere from one time to another. Because of many variables, it may not be practical to determine an a atmospheric correction directly, but a combination of dark object subtraction and band ratios may provide an adequate correction. The other major problem is that a backscattered flux may represent a mix of water colour, bottom reflectance, turbidity produced by plankton, and turbidity caused by suspended sediment. In many cases, however, a change in flux is caused simply by a change in the concentration of one constituent.

An optical measure of water colour and turbidity can be obtained with remote sensing. Pollutants must affect colour or turbidity to be detectable, although dissolved luminescent constituents can be detected by Fraunhofer line discrimination techniques. Dissolved coloured materials increase the absorption of light in water and decrease the remote signal. Suspended materials increase the backscatter of light and increase the remote signal.

Most studies which obtained good correlation between remotely sensed radiance and concentration data from ships included a calibration of the radiance values based on water sample analyses for sediment concentration, size distribution and composition.98/ 18/ 96/ 100/ 101/ 102/ Because sediment concentration is not uniquely related to backscattered radiance, a prior knowledge of grain size, composition and layering is required before radiance maps can be converted into suspended sediment concentration maps.103/ 104/ 97/ Considerable progress is being made in the development of optical models of the water column to discriminate organic from inorganic suspended matter, to map substances having varying concentrations (layers) as a function of depth, to eliminate bottom reflections, and to improve atmospheric corrections.105/ 106/ The same discussion applies to mapping pollutant concentrations, good ground measurements are required and fairly sophisticated data analysis techniques may have to be used with multispectral scanner data.105/ 107

Chlorophyll concentration strongly influences ocean colour and is a good indicator of coastal productivity.106/ The Coastal Zone Color Scanner (CZCS) on Nimbus 7 has been used with considerable success to map ocean colour and chlorophyll-a concentrations over open ocean areas.108/ Despite difficult

atmospheric corrections, chlorophyll-a concentrations have been mapped with considerable accuracy.109/ In turbid coastal waters, it is more difficult to map chlorophyll concentrations using passive techniques. Water masses dominated by dissolved carbon, particulate carbon and inorganic sediment have been differentiated with aircraft multispectral scanners.110/ Principal component analysis techniques have also been effective for identifying estuarine water types.111/

Estuarine waters typically contain high concentrations of dissolved and suspended materials which arise from or have an impact on biological activity in the water. These substances may also, in some cases, be used as tracers to study circulation patterns in the estuary. Many of these materials are optically active and have an influence on the spectral and angular distribution of the light in the water column. As a result, measurements of the spectral characteristics of the light within the water column and above the surface may be used to determine the concentrations of various materials in the water. Ideally, this should be done with remote measurements of the reflected light, so that the rapid, large-scale sampling capabilities provided by aircraft or satellite sensors can be utilized. However, to interpret these remote measurements, more information about the optical properties of each of the important water constituents is needed. This information must be obtained by in situ measurements.

In a Government-sponsored investigation by our Center of Remote Sensing, sediment and nutrient-laden Delaware Bay waters are being sampled repetitively to assess the concentrations and total amounts of key optical constituents such as phytoplankton pigments, dissolved organic compounds, sediment and detrital matter. The study relies on accurate biological and chemical analyses on water samples as well as in situ measurements of light profiles in the water column. Such measurements are performed by lowering a LICOR 1800-UW underwater radiometer from the ship and recording a narrow-band (10 nm) irradiance spectrum at a series of depths in the water column. The optical measurements allow determination of wavelength-specific attenuation and backscatter coefficients as well as calculation of surface and below-surface reflectance. By combining the optical parameters with the biological and chemical data it is possible to characterize a water mass in terms of its spectral signature and to pinpoint the constituents responsible for it in virtually every case.

Our modeling effort is an extension of the singly scattered irradiance (SSI) model developed at the College of Marine Studies by Dr. William Philpot. The goal of the present study is to invert this model so that optically important constituent concentrations can be inferred from spectral reflectance measured by remote sensing instruments. The results of this study allow new applications of remote sensing data to estuarine research as well as provide a new monitoring tool for estuarine management.

Chlorophyll and other pigments have also been detected in turbid coastal waters using laser fluorosensing techniques. Chlorophyll concentrations and dispersed oil can be determined using low altitude airborne lasers operating in the fluorosensing mode.112/ 113/ Oil slicks which have not been emulsified and mixed in the water column can be mapped with film cameras, multispectral

scanners, and thermal infra-red and microwave devices.114/ In the visible region, oil has a higher index of refraction than background water; in the thermal infra-red and microwave banks, its emissivity differs from that of water. Radar can detect it primarily because oil slicks dampen small surface waves. However, only microwave devices and laser fluorosensors offer hope for measuring oil slick thickness.

Thermal infra-red scanners have been very effective for mapping ocean surface temperatures with about +1°C accuracy and for studying coastal surface currents.115/ Thermal infra-red scanners on NOAA satellites, together with multispectral scanners such as the AVHRR and CZCS, have been used to study coastal upwelling and estuarine properties.74/ 79/ Productive coastal upwelling events are accompanied by drops in temperature and chlorophyll-induced colour changes detectable by AVHRR and CZCS.

Large area measurements of ocean salinity are of considerable value to oceanographers investigating the coastal zone. Such data are useful in determining the estuarine impact of river flooding for shellfish bed health monitoring and in detecting coastal water masses where mixing of different bodies of water occur that could affect fish distribution. Changes in salinity and temperature patterns can identify the presence of large scale turbulence and currents. The data are also useful in refining circulation and pollution models in bay areas. However, salinity is one of the most difficult properties to sense remotely. L-band microwave radiometers employed from low altitude aircraft have been able to map salinity with an accuracy of less than 1 part per 1,000 at 25°C. Such accuracy is useful for estuarine studies where large salinity gradients can be found. Open-ocean salinity sensing requirements are more stringent by at least one order of magnitude. One of the principal needs relates to the measurement of mass density, as inferred from simultaneous temperature and salinity measurements. Such data identify regions of upwelling and circulation patterns.

Coastal wave conditions and wave spectra are best obtained using laser profilers from aircraft, radar mappers and radar altimeters.116/ 117/ 118/ 119/ Imagers such as synthetic aperture radar (SAR) or film cameras are particularly effective for wave studies if the data is analyzed using Fournier analysis techniques.120/ Because surface winds induce capillary waves that influence microwave emission and reflectance, microwave sensors, particularly radar scatterometers such as those on Seasat, have been tested for surface wind determinations.117/ Seasat sensors were specifically designed for measuring and mapping ocean waves, surface winds, currents and other features.121/ The accuracies of the measurements are remarkable, considering they were made from satellite altitudes.

CONCLUSIONS AND FUTURE NEEDS

As shown in table 3, remote sensors on satellites and aircraft are capable of measuring many properties of coastal waters, tidal wetlands and estuaries. Landsat MSS and TM, NOAA AVHRR, Nimbus CZCS and Seasat have been major contributions to coastal investigations.

As low-cost microcomputers with user-friendly software become available for analysing imagery, data from these satellites are being more widely used in coastal and estuarine projects throughout the world. However, many improvements are needed if user requirements are to be fully satisfied in the future. The following are some obvious areas for improvement.

(1) None of the available satellite systems have both the required spatial and temporal resolution for observing tidal-induced processes in estuaries and coastal waters. Synchronous orbit satellites have sufficient temporal resolution, while Landsat and SPOT sensors have enough spatial resolution. Only aircraft can provide both at the present time.

(2) Electromagnetic sensors have insufficient depth penetration, particularly in turbid coastal waters, for bathymetric or other studies. Although powerful laser profilers can penetrate to several Secchi depths, shipborne sonar profilers must still frequently be used to supplement EM wave techniques.

(3) Chlorophyll and suspended sediment techniques need to be further developed to improve their accuracy to better than the factor 2 available at present. Multispectral techniques for differentiating dissolved organics, particulate organics and inorganic sediment in estuaries need to be further refined. A dedicated aircraft with a multispectral scanner having bands somewhat similar to the CZCS is required.

(4) Water salinity is one of the most important parameters to be measured in estuaries. Microwave radiometers are capable of resolving salinity down to 1 part per 1,000, which is useful but not sufficient. For estuarine and coastal studies, accuracies down to 0.1 part per 1,000 are sought.

(5) Seasat's microwave sensors provided large amounts of valuable data on coastal waves, currents, surface winds and other properties. However, Seasat survived only for three months. An aircraft or a similar satellite with higher resolution sensors is needed to provide data for estuarine and coastal investigations of surface winds, currents and wave spectra.

(6) Underwater cameras and sonar systems have been successfully deployed to map bottom features, submerged aquatics, fish schools, waste dispersion, thermoclines and fronts in relatively clear lake or shelf waters. These devices must be modified to be usable in turbid estuaries exhibiting more bottom variability, current fluctuations and stronger gradients in the water column.

Table 3. PERFORMANCE OF REMOTE SENSORS FOR ESTUARINE STUDIES

Sensor	Platform	Veg.& Land Use	Biomass & Veg. Stress	Coast-line Erosion	Bottom Feat. SAV	Depth Profiles	Susp. Sed. Ptrns.	Susp. Sed. Concen.	Chloro-phyll Concen.	Oil Slicks	Surf. Temp.	Water Sal.	Curr. Circ. Ptrns.	Wave Spectra	Surf. Winds
Film Cameras	A	3	2	3	3	2	2	1	1	2	0	0	2	2	1
	S	2	1	2	2	1	2	1	1	1	0	0	2	2	1
Multispectral Scanners	A	3	2*	3	3	2	3	2*	2*	3	0	0	2	2	1
	S	2	1	2	2	2	3	2	2	2	0	0	2	2	1
Thermal IR Scanners	A	1	1	1	0	0	1	0	0	3	3	1	2	0	1
	S	0	0	0	0	0	1	0	0	1	3	0	2	0	1
Laser Profilers	A	0	0	1	2	3	1	0	0	1	0	0	0	3	1
	S	0	0	1	1	1	0	0	0	0	0	0	0	2	0
Laser Fluorosensors	A	1	1	0	0	0	2	2	3	3	1	1	1	0	0
	S	0	0	0	0	0	1	1	1	1	0	0	0	0	0
Microwave Radiometers	A	1	0	0	0	0	1	1	0	2	3	2	2	1	3
	S	0	0	0	0	0	0	0	0	1	2	1	1	0	2
Imaging Radar (SAR or SLAR)	A	2	1	3	0	1	1	0	0	3	1	1	2	3	2
	S	1	0	2	0	1	0	0	0	2	0	0	1	2	1
CODAR (Radar)	C	0	0	0	0	0	0	0	0	0	0	1	3	2	2
PADS(Acoustic)	C	0	0	2	3	3	2	1	0	1	0	0	3	1	0
UW Camera	C	0	0	2	3	2	2	1	1	1	0	0	1	0	0

Rating
3 = Reliable and Available (Operational)
2 = Qualitative and/or Needs Additional Testing
1 = Experimental and/or Not Widely Available
0 = Not Applicable

Platform
A = Aircraft (Medium or Low Altitude)
S = Spacecraft (Satellite)
C = Ground (Boat or Field)

NOTES

1/ Odum, E.P., Basic Ecology, (Philadelphia, Saunders College Publishing, 1983).

2/ Reimold, R.J., and Hardisky, M.A., "Nonconsumptive use values of wetlands", Wetland Functions and Values: The State of Our Understanding, (Minneapolis, MN, Am. Water Res. Asso., 1979).

3/ Darnell, R.M., "Overview of major development impacts on wetlands", Proc. Nat. Wetland Protec. Symp., U.S. Fish Wildl. Serv., Washington, DC, (1978) pp. 19-27.

4/ Haueisen, A.J., "An examination of legislation for the protection of the wetlands of the Atlantic Gulf coast states", Gulf Res. Rep. 4, (1973) pp. 233-263.

5/ Carter, V.P., "Coastal wetlands: role of remote-sensing", Coastal Zone '78, (1978), pp. 1261-1283.

6/ Colwell, R.N., "Basic matter and energy relationships involved in remote reconnaissance", Photogram. Eng. 29 (1963) pp. 761-799.

7/ Colwell, R.N., "Remote sensing of natural resources", Sci. Am. 218, (1968), pp. 54-69

8/ Colwell, R.N., Remote sensing as a means of determining ecological conditions, Bioscience 127, (1967) pp. 444-449.

9/ Shay, J.R., "Remote sensing for agricultural purposes", BioScience 17, (1967), pp. 450-451.

10/ Cameron, H.L., "The use of aerial photography in seaweed surveys", Photogram. Eng. 16, (1950) pp. 493-501.

11/ Schulte, O.W., "The use of panchromatic, infra-red and colour aerial photography in the study of plant distributions", Photogram. Eng. 17., (1951), pp. 688-714.

12/ Stroud, L.M., and Cooper, A.W., "Color-infra-red aerial photographic interpretation and net primary productivity of regularly flooded North Carolina salt marsh", Water Resources Res. Inst., No. 14, (Univ. North Carolina, 1968), p. 86.

13/ Reimold, R.J., Gallagher, J.L., and Thompson, D.E., "Remote sensing of tidal marsh", Photogram. Eng. 39, (1973), pp. 477-488.

14/ Pestrong, R., "Multiband photos for a tidal marsh", Photogram. Eng. 35, (1969), pp. 453-470.

15/ Guss, P., "Tidelands management mapping for the coastal plains region", Am. Soc. Photogram. Proc. Mapping Symp., (Washington, DC, 1972), pp. 243-262.

16/ Russell, O., and Wobber, F.J., "Aerial multiband wetlands mapping", Photogram. Eng. 38, (1972), pp. 1188-1189.

17/ Anderson, R.R., and Wobber, F.J., "Wetlands mapping in New Jersey", Photogram. Eng. 39 (1973) pp. 353-358.

18/ Klemas, V., Daiber, F.C., Bartlett, D.S., Crichton, O., and Fornes, A.O., "Inventory of Delaware's wetlands", Photogram. Eng. 40 (1974) pp. 433-439.

19/ Scarpace, F.L., Kiefer, R.W., Wynn, S.L., Quirk, B.K., and Friederichs, G.A., "Quantitative photo-interpretation for wetland mapping", Proc. 41st Ann. Mtg. Am. Soc. Photogram., (Washington, DC, 1975) pp. 750-771.

20/ Howland, W.G., Multispectral aerial photography for wetland vegetation mapping, Photogram. Eng. Remote Sens. 46 (1980) pp. 87-99.

21/ Egan, W.G., and Hair, M.E., "Automated delineation of wetlands in photo-graphic remote-sensing", Proc. Seventh Int. Symp. Remote Sens. Environ., Ann Arbor, MI, (1971) pp. 2231-2251.

22/ Gallagher, J.L., Reimold, R.J., and Thompson, D.E., "Remote sensing and salt marsh productivity", Proc. 38th Ann. Mtg. Am. Soc. Photogram., Washington, DC, (1972) pp. 338-348; and Gallagher, J.L., Reimold, R.J., and Thompson, D.E., "A comparison of four remote-sensing media for assessing salt marsh productivity", Proc. Eighth Int. Symp. Remote Sens. Environ., Ann Arbor, MI, (1972), pp. 1287-1295.

23/ Reimold, R.J., Gallagher, J.L., and Thompson, D.E., "Coastal mapping with remote sensors", Proc. Coastal Mapping Symp., Am. Soc. Photogram., Washington, DC, (1972) pp. 99-112.

24/ Gallagher, J.L., and Reimold, R.J., Tidal marsh plant distribution and productivity patterns for the sea to freshwater: a challenge in resolution and discrimination, In Fourth Bienn. Wkshop. Aerial Color Photogr. in Plant Sci., (Univ. Maine-Orono, 1973) pp. 165-183.

25/ Gallagher, J.L., "Remote sensing as a tool for studying the ecology of halophytes", Ecology of Halophytes R.J. Reimold and W.H. Queen, eds., (Academic Press, New York, 1974).

26/ Benton, A.R., Hatch, S.L., Kirk, W.L., Newman, R.M., Snell, W.W., and Williams, J.G., Monitoring of Texas coastal wetlands, TR RSC-88, (Texas A&M Univ., College Station, 1977), p. 101.

27/ Schneider, W.J., "Color photographs for water resources", Photogram. Eng. 32 (1966) pp. 958-965.

28/ Schneider, W.J., "Color photographs for water resources", Photogram Eng. 34 (1968) pp. 257-262.

29/ Seher, J.S., and Tueller, P.T., "Color aerial photos for marshland", Photogram. Eng. 39 (1973) pp. 489-499.

30/ Enslin, W.R., and Sullivan, M.C., "The use of colour infra-red photography for wetlands assessment", Remote Sensing of Earth Resources, F. Shahrokhi, ed., (Univ. Tennessee, Tullahoma, 1974) pp. 697-719.

31/ Cowardin, L.M., and Meyers, V.I., "Remote sensing for identification and classification of wetland vegetation", J. Wildl. Mgt. 38 (1974) pp. 308-314.

32/ Shima, L.J., Anderson, R.R., and Carter, V.P., "The use of aerial colour infra-red photography in mapping the vegetation of a freshwater marsh", Chesap. Sci. 17 (1976) pp. 74-89.

33/ Carter, V.P., Malone, D.L., and Burbank, J.H., Wetland classification and mapping in western Tennessee, Photogram. Eng. Remote Sens. 45 (1979) pp. 273-284.

34/ Stewart, W.R., Carter, V., and Brooks, P.D., "Inland (non-tidal) wetland mapping", Photogram. Eng. Remote Sens. 46 (1980) pp. 617-628.

35/ Gammon, P.T., and Carter, V., "Vegetation mapping with seasonal colour infra-red photographs", Photogram. Eng. Remote Sens. 45 (1979) pp. 87-97.

36/ Anderson, R.R., Carter, V., and McGinness, J., Mapping southern Atlantic coastal wetlands, South Carolina-Georgia, using ERTS-1 imagery, In Remote Sensing of Resources, F. Shahrokhi, ed., (University of Tennessee, Tullahoma, 1973) pp. 1021-1028.

37/ Carter, V.P., and Schubert, J., "Coastal wetlands analysis for ERTS MSS digital data and field spectral measurements", Proc. Ninth Int. Symp. Remote Sens. Environ., Ann Arbor, MI, 1974) pp. 1241-1260.

38/ Klemas, V., Daiber, F.C., Bartlett, D.S., and Rogers, R.H., "Coastal zone classification from satellite imagery", Photogram. Eng. Remote Sens. 41 (1975) pp. 499-513.

39/ Butera, M.K., "A determination of the optimum time of year for remotely classifying marsh vegetation from Landsat multispectral scanner data", NASA TM 58212, (NSTL Station, MS, 1978) p. 14.

40/ Lyon, J.G., "Remote sensing analyses of coastal wetlands characteristics: The St. Clair Flats, Michigan", Proc. Thirteenth Int. Symp. Remote Sens. Environ., Ann Arbor, MI, (1979) pp. 1117-1129.

41/ Lyon, J.G., An analysis of vegetation communities in the lower Columbia River Basin, Michigan Sea Grant MICHU-SG-79-311, Ann Arbor, MI (1979) p. 7. 42/ Gilmer, D.S., Work, E.A., Colwell, J.E., and Rebel, D.L., "Enumeration of praire wetlands with Landsat and aircraft data", Photogram. Eng. Remote Sens. 46 (1980) pp. 631-634.

43/ Garret, M.K., and Carter, V., Contribution of remote-sensing to habitat evaluation and management in a highly altered ecosystem, In Trans. 42nd No. Am. Wildl. Nat. Res. Conf., (Washington, DC., Wildl. Mgt. Ints., 1977) pp. 56-65.

44/ Carter, V.P., Garret, M.K., Shima, L., and Gammon, P., "The Great Dismal Swamp: management of hydrologic resource with the aid of remote sensing", Water Res. Bull. 13 (1977) pp. 1-12.

45/ Thompson, D.E., Ragsdale, J.E., Reimold, R.J., and Gallagher, J.L., Seasonal aspects of remote-sensing coastal resources, In Remote Sensing of Earth Resources, F. Shahrokhi, ed., (Univ. Tennessee, Tullahoma, Tn., 1973) pp. 1201-1249.

46/ McEwen, R.B., Kosco, W.J., and Carter, V., Coastal wetland mapping, Photogram. Eng. Remote Sens. 42 (1976) pp. 221-232.

47/ Masry, S.E., and MacRitchie, S., "Different considerations in coastal mapping", Photogram. Eng. Remote Sens. 46 (1980) pp. 521-528.

48/ Penney, M.E., and Gordon, H.H., Remote sensing of wetlands in Virginia, Proc. Tenth Int. Symp. Remote Sens. Environ., (Ann Arbor, MI, (1975) pp. 495-503.

49/ Thomas, J.R., Wiegand, C.L., and Meyers, V.I., Reflectance of cotton leaves and its relation to yield, Agron. J. 59 (1967) pp. 551-554.

50/ Gausman, H.W., Allen, W.A., and Cardenas, R., "Reflectance of cotton leaves and their structure", Remote Sens. Environ. 1 (1969) pp. 19-22.

51/ Sinclair, T.R., Hoffer, R.M., and Schreiber, M.M., "Reflectance and internal structure of leaves from several crops during a growing season", Agron. J. 63 (1971) pp. 864-868.

52/ Gausman, H.W., "Leaf reflectance of near-infra-red, Photogram. Eng. 40 (1974) pp. 183-191.

53/ Carter, V.P., and Anderson, R.R., "Interpretation of wetlands imagery based on spectral reflectance characteristics of selected plant species", Proc. Am. Soc. Photogram., (1972) pp. 580-595.

54/ Pfeiffer, W.J., Linthurst, R.A., and Gallagher, J.L., Photographic imagery and spectral properties of salt marsh vegetation as indicators of canopy characteristics, In Proc. Am. Soc. Photogram., (Falls Church, VA, 1973) pp. 1004-1015.

55/ Bartlett, D.S., and Klemas, V., Assessment of tidal wetland habitat and productivity, In Proc. Thirteenth Int. Symp. Remote Sens. Environ., (Ann Arbor, MI, 1979) pp. 693-701.

56/ Klemas, V., and Ackleson, S.G., "Remote reconnaissance of submerged aquatic vegetation: A radiative transfer approach", Proc. Third Landsat-4 Wkshop., (NASA GSFC, Greenbelt, MD, 1983).

57/ Jordon, C.F., "Derivation of leaf area index from quality of light on the forest floor", Ecology 50 (1969) pp. 663-666.

58/ Marshall, D.E., "Characteristics of Spartina marsh which is receiving treated municipal sewage waters", Studies of Marine Estuarine Ecosystems Developing With Treated Sewage Wastes, H.T. Odum and A.F. Chestnut, eds., Nat. Sci. Fdn., Washington, DC, 1970).

59/ Tucker, C.J., Miller, L.D., and Pearson, R.L., "Measurement of the combined effect of green biomass, chlorophyll and leaf water on canopy spectroreflectance of the shortgrass prairie", Remote Sensing of Earth Resources, F. Shahrokhi, ed., (Univ. Tennessee, Tullahoma, TN, 1973) pp. 601-627.

60/ Pearson, R.L., Miller, L.D., and Tucker, C.J., Hand-held spectral radiometer to estimate graminoous biomass, Appl. Opt. 15 (1976) pp. 416-418.

61/ Bartlett, D.S. , Variability of wetland reflectance and its effect on automatic categorization of satellite imagery, (Master's thesis, Univ. Delaware, Newark, 1976) p. 108.

62/ Drake, B.G., Seasonal changes in reflectance and standing crop biomass in three salt marsh communities, Plant Physiol. 58 (1976) pp. 696-699.

63/ Bartlett, D.S., Spectral reflectance of tidal wetland plant canopies and implications for remote-sensing, Doctoral dissertation, (Univ. Delaware, Newark, 1979) p. 239.

64/ Bartlett, D.S., and Klemas V., Quantitative assessment of tidal wetlands using remote-sensing, Environ. Mgt. 4 (1980) pp. 337-345.

65/ Bartlett, D.S., and Klemas V., In situ spectral reflectance studies of tidal wetland grasses, Photogram. Eng. Remote Sens. 47 (1981) pp. 1695-1703.

66/ Jensen, A., "Seasonal changes in near infra-red reflectance ratio and standing crop biomass in a salt marsh community dominated by Halimione portulacoides (L.) Aellen", New Phytol. 86 (1980) pp. 57-67.

67/ Curran, P.J., "Multispectral photographic remote-sensing of vegetation amount and productivity", Proc. Fourteenth Int. Symp. Remote Sens., (Ann Arbor, MI, 1980) pp. 623-637.

68/ Curran, P.J., "Multispectral photographic remote-sensing of green vegetation biomass and productivity", Photogram. Eng. Remote Sens. 48 (1982) pp. 243-250.

69/ Best, R.G., Wehde, M.E., and Linder, R.L., "Spectral reflectance of hydrophytes", Remote Sens. Environ. 11 (1981) pp. 27-35.

70/ Earnst-Dottavio, C.L., Hoffer, R.M., and Mroczynski, R.P., Spectral characteristics of wetland habitats, Photogram. Eng. Remote Sens. 47 (1981) pp. 223-227.

71/ Budd, J.T.C., and Milton, E.J., "Remote sensing of salt marsh vegetation in the first four proposed thematic mapper bands", Int. J. Remote Sens., 3 (1982) pp. 147-161.

72/ Hardisky, M.A., Smart, R.M., and Klemas, V., "Seasonal spectral characteristics and aboveground biomass of the tidal marsh plant", Spartina alterniflora, Photogram. Eng. Remote Sens. 49 (1983) pp. 85-92.

73/ Gross, M.F., Hardisky, M.A., Klemas, V., and Wolf, P.L., Quantification of biomass of the marsh grass Spartina alterniflora using Landsat thematic mapper imagery. Photogram. Eng. Remote Sens. 53(11) (1987) pp. 1577-1583.

74/ Hardisky, M.A., Klemas V., and Smart, R.M., The influence of soil salinity, growth form and leaf moisture on the spectral radiance of Spartina alterniflora canopies, Photogram. Eng. Remote Sens. 49 (1983) pp. 77-83.

75/ Hardisky, M.A., Smart, R.M., and Klemas, V., Growth response and spectral characteristics of a short Spartina alterniflora salt marsh irrigated with freshwater and sewage effluent, Remote Sens. Environ. 13 (1983) pp. 57-67.

76/ Hardisky, M.A., Klemas, V., and Daiber, F.C., Remote sensing salt marsh biomass and stress detection, Advances in Space Research, vol. 2, COSPAR, (Pergamon Press, London, 1983) pp. 219-229.

77/ Klemas, V., Remote sensing of coastal fronts and their effects on oil dispersion, Int. J. Remote Sens. 1(1) (1980) pp. 11-28.

78/ Gagliardini, D.A., Karszenbaum, H., Legeckis, R., and Klemas, V. , Application of Landsat MSS, NOAA/TIROS AVHRR and Nimbus CZCS to study the La Plata River and its interaction with the ocean, Remote Sens. Environ. 15 (1984) pp. 21-36.

79/ Karszenbaum, H., Gagliardini, D.A., Klemas V., Dominguez, F., and Legeckis, R., "The applicability of TIROS-N/NOAA Advanced Very High Resolution radiometer data to studies of large estuaries", Seventeen Int. Symp. Remote Sens. Environ., (Ann Arbor, MI 1983)

80/ Schuchman, R.A., Rufenach, C.L., Gonzalez, F.I., and Klooster, A., "The feasibility of measurement of ocean surface currents using synthetic aperture radar, Proc. Thirteenth Int. Symp. Remote Sens. Environ., (Ann Arbor, MI, 1979)

81/ Barrick, D.E., Evans, M.E., and Weber, B.L., "Ocean surface currents mapped by radar", Science 198 (1977) pp. 138-144.

82/ Klemas, V., Mauer, D., Leatham, W., Kinner, P., and Treasure, W. , Dye and drogue studies of spoil disposal and oil disperson, J. Water Poll. Control Fed. 46(8) (1974) pp. 2026-2034.

83/ Klemas, V., Davis, G., Lackie, J., Whalen, W., and Tornatore, G. , Satellite, aircraft and drogue studies of coastal currents and pollutants, IEE Trans. Geosci. Electron., GE-15(2) (1977) pp. 97-108.

84/ Keller, M., Tidal current survey by photogrammetric methods, Photogram. Eng. 29(5) (1963) pp. 824-832.

85/ Dolan, R., Coastal properties, Photogram. Eng. 39(2) (1973) pp. 255-260.

86/ Dolan, R., Hayden, B., Heywood, J., and Vincent, L., Shoreline forms and shoreline dynamics, Science 197 (1977) pp. 49-51.

87/ Stafford, D.B., and Langfelder, J., Air photo survey of coastal erosion, Photogram. Eng. 37(6) (1971) pp. 565-575.

88/ Rogers, R.H., Lyzenga, D.R., and Wilson, D.L., "Mapping water depth and land features in the coastal zone by processing of Landsat MSS data", Proc. Int. Symp. Remote Sens. Environ., First Thematic Conf., (Cairo, Egypt, 1982) pp. 425-427.

89/ Lyzenga, D.R., "Passive remote-sensing techniques for mapping water depth and bottom features", Appl. Opt. 17(3) (1978) pp. 379-384.

90/ Lyzenga, D.R., "Shallow water reflectance modeling with applications to remote-sensing of the ocean floor", Proc. Thirteenth Int. Symp. Remote Sens. Environ., (Ann Arbor, MI, 1979) pp. 23-27.

91/ Hoge, F.E., Swift, R.N., and Frederick, E.B., "Water depth measurement using an airborne pulsed neon laser system", Appl. Opt. 19(6) (1980).

92/ Link, L.E., Krabill, W.B., and Swift, R.N., A prospectus on airborne laser mapping systems, Proc. 24th Plenary Mtg., COSPAR Wkshop. on the selection and impact of spectral bands for each resources analysis from space, (Ottawa, Ontario, Canada, 1982).

93/ Smith, P.F., Underwater Photography -- Scientific and Engineering Applications, (Van Nostrand Reinhold, Publ., New York, 1984) p. 422.

94/ Proni, J.R., Newman, F.C., Sellers, R.L., and Parker, C., Acoustic tracking of ocean-dumped sewage sludge, Science 193 (1976) pp. 1005-1007.

95/ Wirtz, A.R., and Acker, W.C., "A versatile sonar system for fisheries research and management applications", IEEE Reprint from Oceans '79 Conf. Record, (Seattle, Wa., BioSonics, Inc. 1979).

96/ Johnson, R.W., "Quantitative suspended sediment mapping using aircraft remotely sensed multispectral data", Earth Res. Survey Symp., Houston, Tx., 1975.

97/ Moore, G.K., "Satellite surveillance of physical water-quality characteristics", Proc. Twelfth Int. Symp. Remote Sens. Environ., (1978) pp. 445-462.

98/ Munday, J.C., and Alfoldi, T.T., "Landsat test of diffuse reflectance models for aquatic suspended solids measurements", Remote Sens. Environ. 8 (1979) pp. 169-183.

99/ Maul, G.A., Charnell, R.L., and Qualset, R.H., "Computer enhancement of ERTS-1 images for ocean radiances", Remote Sens. Environ. 3 (1974) pp. 237-254.

100/ Ritchie, J.C., Schieve, F.R., and McHenry, J.R., "Remote sensing of suspended sediments in surface waters", Photogram. Eng. Remote Sens. 42(12) (1976) pp. 1539-1545.

101/ McKim, H.L., Merry, C.J., and Layman, R.W., "Remotc sensing of water using an airborne spectroradiometer", Proc. Fourteenth Int. Symp. Remote Sens. Environ., San Jose, Costa Rica, (1980) pp. 1353-1362.

102/ McKim, H.L., Merry, C.J., and Layman, R.W., "Water quality monitoring using an airborne spectroradiometer", Photogram. Eng. Remote Sens. 50(3) (1984) pp. 353-360.

103/ Amos, C.L., and Alfoldi, T.T., "The determination of suspended sediment concentrations in a macro-tidal system using Landsat data", J. Sed. Petrol. 49 (1979) pp. 159-173.

104/ Whitlock, C.H., Kuo, C.Y., and LeCroy, S.R., "Criteria for the use of regression analysis for remote-sensing of sediment and pollutants", Remote Sens. Environ. 12 (1982) pp. 151-168.

105/ Philpot, W.D., and Ackleson, S.G., Remote sensing of optically shallow, vertically inhomogeneous waters: A mathematical model, Sea Grant Rpt. DEL-SG-12-81, (Univ. Delaware, Newark, 1981).

106/ Wilson, W.H., and Austin, R.W., "Remote sensing of ocean colour", Ocean Opt. Vm, SPIE 160 (1978) pp. 23-30.

107/ Klemas, V., and Philpot, W., "Drift and dispersion studies of ocean-dumped waste using Landsat imagery and current drogues", Photogram. Eng. Remote Sens. 47(4) (1981) pp. 533-542.

108/ Hovis, W.A., Jr., Remote sensing of water pollution, Proc. Eleventh Int. Symp. Remote Sens. Environ., (Ann Arbor, MI, 1977) pp. 361-362.

109/ Gordon H.R., and Clark, D.K., Atmospheric effects in the remote-sensing of phytoplankton pigments, Boundary Layer Meteorol. 18 (1980) pp. 299-313.

110/ Klemas, V., Daiber, F.C., Philpot, W.D., Ackleson, S.G., and Roman, C.T., Remote sensing of organic/inorganic materials in coastal and estuarine waters, Final Rpt. Proj. R/B under Sea Grant NA80-AA-D-0016, (Univ. Delaware, Newark, 1981).

111/ Stumpf, R.M., Analysis of suspended sediment distributions in the surface waters of Delaware Bay using remote-sensing of optimal properties, Doct. Dissert., EUniv. Delaware, Newark, DE, 1984).

112/ Jarrett, O., Jr., Brown, C.A., Jr., Campbell, J.W. Houghton, W.M., and Poole, L.R., Measurement of chlorophyll fluorescence with an airborne fluorosensor, Proc. Thirteenth Int. Symp. Remote Sens. Environ., (Ann Arbor, MI, 1979).

113/ O'Neil, R.A., Buja-Bijunas, L., and Bayner, D.M., "Field performance of a laser fluorosensor for the detection of oil spills", Appl. Opt. 19(6) (1980).

114/ Catoe, C.E., "The applicability of remote-sensing techniques or oil slick detection", Offshore Tech. Conf. Paper OTC 1606, (Dallas, TX, 1972).

115/ Legeckis, R., Application of synchronous meteorological satellite data to the study of time dependent sea surface temperature changes along the boundary of the Gulf Stream, Geophys. Res. Ltrs. 2(10) (1975) and Legeckis, R., A survey of world-wide sea surface temperature fronts detected by environment satellites, J. Geophys. Res. 83(C9) (1978).

116/ Panicker, N.N., "Review of techniques for directional wave spectra", In Proc. Int. Symp. Ocean Wave Meas., ASCE (1974).

117/ Ross, D.B., Cardone, V.J., and Conaway, J.W., Jr., Laser and microwave observations of sea-surface conditions for fetchlimited 17- to 25-m/s winds, IEEE Trans. Geosci. Electron. GE-8(4) (1970) pp. 326-336.

118/ Born, G.H., Dunne, J.A., and Lane, D.B., "Seasat mission overview, Science, 204 (1979)".

119/ Schule, J.J., Simpson, L.S., and DeLeonibus, P.S., "A study of fetchlimited wave spectra with an airborne laser", J. Geophys. Res. 76 (1971) pp. 4160-4171.

120/ Stilwell, D., "Directional energy spectra of the sea from photographs", J. Geophys. Res. 74(8) (1969) pp. 1974-1986.

121/ American Geophysical Union, Seasat Special Issue II: Scientific Results, Washington, D.C. (1983)